N73 15595

NASA CR-121116

CONSIDERATION OF MATERIALS FOR AIRCRAFT BRAKES

MARSHALL B. PETERSON
TING-LONG HO

TRIBOLOGY LABORATORY
MECHANICS DIVISION
RENSSELAER POLYTECHNIC INSTITUTE
TROY, NEW YORK 12181

April 1972

CASE FILE
COPY

Prepared for
AEROSPACE SAFETY RESEARCH AND DATA INSTITUTE
LEWIS RESEARCH CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CLEVELAND, OHIO 44135

UNDER

NASA GRANT NGR 33-018-152

C. DAVID MILLER, TECHNICAL MONITOR

R.L. JOHNSON, TECHNICAL ADVISOR

N73-15595

ERRATUM SHEET

NASA CR-121116
"Consideration of Materials for Aircraft Brakes"

The designation "cn" in the above report refers to "centimeter".

To Rent 3-19-73

Tribology Laboratory
Mechanics Division
Rensselaer Polytechnic Institute
Troy, New York 12181

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-121116		

4. Title and Subtitle	5. Report Date
Consideration of Materials for Aircraft Brakes	April 1972
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
M.B. Peterson and Ting-Long Ho	
	10. Work Unit No.

9. Performing Organization Name and Address	11. Contract or Grant No.
Rensselaer Polytechnic Institute Troy, New York 12181	NGR 33-018-152
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Contractor Report
National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Sponsored by Aerospace Safety Research and Data Institute Lewis Research Center
C. David Miller - Technical Monitor
R.L. Johnson - Technical Advisor

16. Abstract

An exploratory investigation was conducted concerning materials and their properties for use in aircraft brakes. Primary consideration was given to the heat dissipation and the frictional behavior of materials. Used brake pads and rotors were analyzed as part of the investigation. A simple analysis was conducted in order to determine the most significant factors which affect surface temperatures. It was found that where size and weight restrictions are necessary, the specific heat of the material, and maintaining uniform contact area are the most important factors. A criterion was suggested for optimum sizing of the brake disks. Bench friction tests were run with brake materials. It was found that there is considerable friction variation due to the formation and removal of surface oxide films. Other causes of friction variations are surface softening and melting. The friction behavior at high temperature was found to be more characteristic of the steel surface rather than the copper brake material. It is concluded that improved brake materials are feasible.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Brake materials Surface temperature Friction and wear	Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	73	$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

FOREWORD

This work was conducted as part of NASA Grant NGR 33-018-152 from the Office of University Affairs, Washington, D.C. 20546. Mr. C. David Miller of NASA's Aerospace Safety Research and Data Institute was the technical monitor. Mr. R.L. Johnson, Manager of NASA's Lubrication Research Branch was the technical advisor. Dr. F.F. Ling, Chairman of RPI's Mechanics Division was the principal investigator. Acknowledgement is made of the many helpful suggestions made by C. David Miller and R.L. Johnson of NASA during the course of this investigation.

CONTENTS

Section		Page
1	SUMMARY	1
2	INTRODUCTION	2
3	RESULTS AND DISCUSSION OF RESULTS	5
	3.1 Friction Temperature Behavior of Materials	5
	3.2 Dissipation of Frictional Heat	9
	3.3 Used Pad Examination	26
	3.3.1 Surface Condition	26
	3.3.2 Metallographic Study of Cross Section	28
	3.4 Frictional Behavior of Brake Materials	43
	3.4.1 Introduction	43
	3.4.2 Apparatus	43
	3.4.3 Simulation	45
	3.4.4 Materials	45
	3.4.5 Reproducibility	47
	3.4.6 Frictional Behavior of Brake Materials	51
	3.4.7 Frictional Behavior with Oxidation Resistant Steels	61
	3.4.8 The Effect of Load	61
	3.4.9 Other Materials	61
4	SUMMARY OF RESULTS	67
REFERENCES		70

SECTION 1

SUMMARY

An exploratory investigation was conducted concerning materials and their properties for use in aircraft brakes. The overall objective of the program is to develop improved brake materials primarily from a safety point of view. In this investigation a study was made in order to determine what improvements could be made in present brake materials. Primary consideration was given to the heat dissipation and the frictional behavior of the materials. Used brake pads and rotors, taken from aircraft at overhaul were analyzed to provide additional information on material behavior.

It was found that frictional variations at high temperatures could be the result of three different phenomena: softening, formation of oxides, or melting. Higher melting point, nongalling, high temperature materials are suggested for improved performance.

A simplified analysis was conducted in order to determine the most significant factors which affect surface temperature. Where there are size and weight restrictions the specific heat and maintaining the contact area appear to be the most important factors. A criterion is suggested for choosing the size of the brake disk. This criterion is that the quantity $\left(\frac{\alpha t_{max}}{\ell^2}\right)^{\frac{1}{2}}$ should be approximately equal to 1 (α = differsivity; t_{max} = time at the end of the braking cycle; 2ℓ = disk thickness).

Bench friction tests indicate that there is considerable friction variation with present brake materials. This variation is due to the formation and removal of surface oxide films. The frictional behavior was found to be determined more by the steel rotor surface than by the brake material.

It is concluded that new improved brake materials are needed.

SECTION 2

INTRODUCTION

Aircraft brake materials have more stringent requirements than almost any other sliding component. While absorbing far more energy, the material is expected to maintain high friction to temperatures of 1800°F with little friction variation. Furthermore, the economics demand that the wear be a minimum. This must be accomplished with little or no use of lubricants. Even though the stresses and temperatures are high and cyclic, the materials must resist structural damage from fracture and thermal fatigue.

Brake materials are used under three different sets of operation. In taxi where the brake receives about 1/3 of its wear, the loads are high but the velocity and the sliding time is relatively short. In braking after or during thrust reversal the loads are relatively the same but the velocity is high (initially) and the sliding time is relatively long (10 to 20 sec). However, the most serious condition is in rejected takeoff where the velocity is at a "takeoff" level and only the brakes are used to stop the aircraft. Fortunately very few of these are ever encountered, but when they are the brakes must perform satisfactorily.

A wide variety of materials have been used as brake materials and they have gradually been upgraded as the temperatures have increased. The original materials were organic in nature and filled with cotten or asbestos. Later molded products were introduced with metallic additions of copper. About fifteen years ago metallic base materials were introduced and are currently used on most high performance brakes. They consist of a base material of copper or iron with a variety of additives. The additives are generally SiO_2 or Al_2O_3 to prevent metal transfer, graphite to prevent friction variations, and occasionally inorganic salts to prevent friction reductions at high temperatures. Other metallic additives are used to aid in sintering and to increase high temperature strength. At present both copper base and iron base materials are used. The copper is in most general aircraft usage. Higher temperature iron base materials are currently being developed.

There are many important properties that these brake materials must have. From an economic point of view low wear is desired. Usually most brakes provide some means to measure wear. When the overall wear has reached a certain level the brake is overhauled. New pads are installed and new disks if necessary. Three to four overhauls usually complete the life of the brake.

From a safety point of view several other properties are important. Primarily it is desired to maintain effective braking under any set of conditions which might be encountered. This usually means effective braking to high generated temperatures; friction should remain constant and the materials stable. If friction decreases with temperature (fade) the braking effectiveness is lost; if friction increases with temperature an unstable or runaway condition might result since higher friction would generate higher temperatures which in turn would again increase friction and so on. Eventually a temperature might be reached where, unknown to the operator, surface damage and metal transfer could occur.

Secondly the materials must be able to withstand the temperatures generated by braking. The high thermal stresses should not cause distortion, cracking or checking of the disk. Thermal softening and excessive oxidation are harmful since they lead to increased wear. Another major factor to consider is that of tire "blowout". Excessive heating of the wheel can soften the tire bead. Eventually this may cause the tire to "blow out" on landing or take-off. Actually there is some protection against this occurring since low melting plugs are incorporated into the wheel. But using the plugs provides only momentary protection against the possibly catastrophic effect of a blow out, and may involve destruction of the tire and down time for the aircraft.

Another important safety aspect of friction is induced friction vibrations which is known as squeal. The noise is not the main concern but the vibrations could cause structural damage in the brake of landing gear area. The extent of such vibration is a function of the friction-velocity behavior and the elasticity of the system.

Thus it can be seen that the friction behavior of brake materials is an important safety aspect from several different points of view. Materials are desired which maintain constant friction to as high a temperature as possible. To do this four different approaches can be used:

- Find the means to stabilize the friction to the maximum temperatures encountered in braking ($\sim 1000^{\circ}C$) using current materials.
- Find means to minimize the interface temperature due to friction.
- Develop materials which will withstand the higher temperatures.
- Develop auxiliary cooling schemes.

In the present investigation efforts were concentrated on the first two approaches in order to determine what, if any, improvements could be made with the present materials. It was hoped that these initial investigations would also suggest improved new materials. Some further discussions of these two approaches are given in the following sections.

SECTION 3

RESULTS AND DISCUSSION OF RESULTS

3.1 Friction Temperature Behavior of Materials

The friction coefficient changes considerably as the temperature is raised. For most materials one of two types of behavior can be found (Fig.1). Friction decreases slightly up to a certain temperature and then increases, at this point metal transfer occurs. The increase in friction is due to the increased ductility of the material (Ref. 1) and usually takes place near the recrystallization temperature of the metal where softening occurs. This increase at T_R has been found for metals, plastics, ceramics and cermet materials with, of course, different values of T_R. Another difference between materials is illustrated by curves "A" and "B", that is, some materials (curve "B") give higher friction and galling. In curve "A" there is low adhesion and no metal transfer up to T_R. In curve "B" there is welding at the points of contact and "junction growth" up to T_R where the asperity junctions coalesce to encompass the whole junction. Below T_R their growth is limited by the work hardening of the material. Most of the commonly used metals (Fe, Cu, Al, Ni and Stainless Steel) behave like curve "B" while certain metals (tool steels, silver, cobalt, and several others) ceramics, cermets, and plastics behave like curve "A". If some means can be devised to prevent the strong adhesion, the "B" type metals will give "A" behavior. The same result will take place with reduced ductility. The "A" curve is, of course, preferred and no sliding systems, brake or otherwise, could function with "B" materials alone. Additives or coatings must be used to improve their sliding characteristics.

The second factor affecting frictional behavior at higher temperatures is the formation of oxide film. Although extensive studies have not been conducted it is known that in most cases the formation of oxide films lowers friction appreciably. This is most obvious with the "B" metals but is also true of "A" metals. Thus a curve like that shown in Figure 2 is often seen. This presumes that some means has been found to transform the "B" type material to an "A" type. The bulk softening of the metal causes the disruption of the oxide and again a rise in friction at T_R. Thus the oxide film is

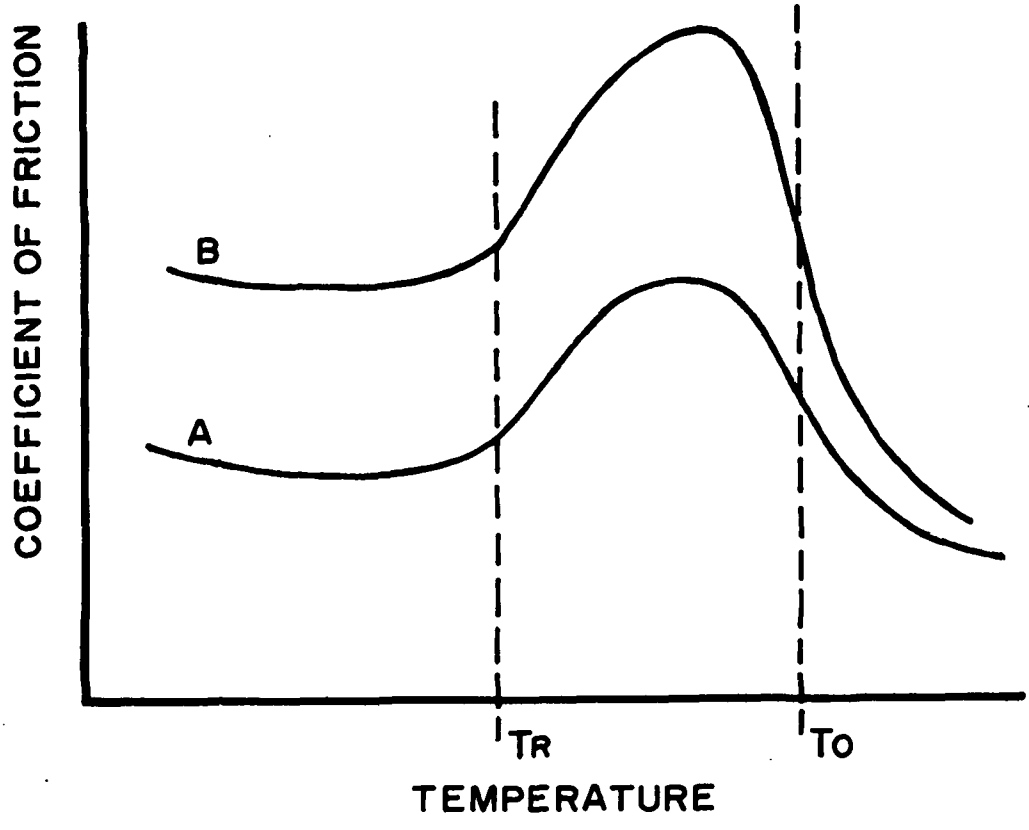


Figure 1. Effect of Temperature on the Coefficient of Friction for Two Different Types of Materials A and B

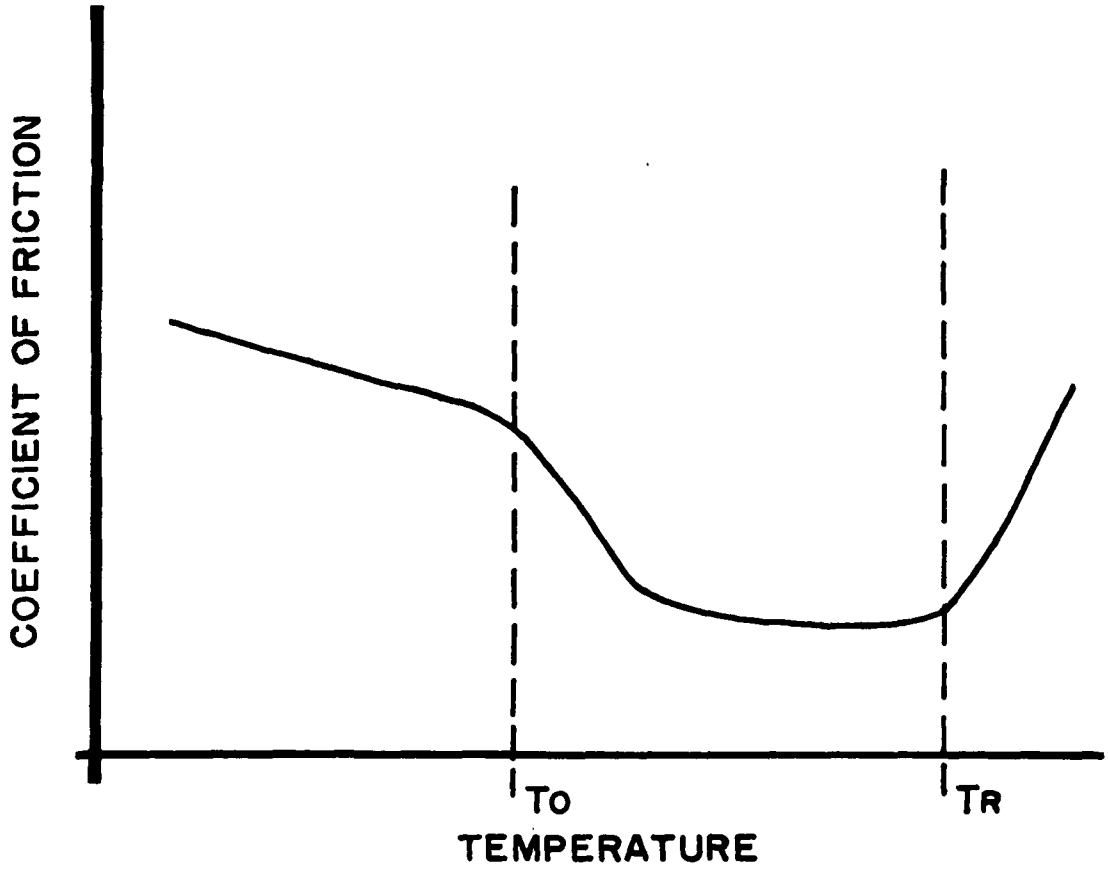


Figure 2. Effect of Temperature on the Coefficient of Friction when Oxidation of the Surface Takes Place

desirable in that it reduces the adhesion between the surfaces, however too much oxidation increases the wear.

Another consideration of importance is the stability of the oxide film. Many oxide films are effective at the temperature at which they are formed but are flaked off the surface if the temperature changes (Ref. 2). This is a function of the relative properties of the oxide and base and the method of oxidation. If oxygen diffuses into the metal surface a relatively stable oxide is formed whereas if the metal diffuses, the oxide is less stable. Soft oxides have been found to be much more stable than harder oxides. Thus once the oxide is formed it may or may not stay on the surface as conditions are changed.

The melting point of the material is also important. Many investigations have shown that as the interface temperatures approach the vicinity of the melting point friction is drastically reduced. To prevent this, higher melting point materials can be used or ways must be devised to remove the melted material.

Based on this discussion it is clear that stable friction values could be obtained by selecting materials which retained their hardness and did not oxidize at high temperatures. Conversely, one could find materials which had stable oxides which dominated friction over the whole temperature range. This second approach could be accomplished with higher temperature materials or with additions of chromium (oxidation resistance) or molybdenum (stabler oxide) or other additions to the present materials. It is also possible that even with the present materials some design or surface modification could be used to prevent or induce oxidation (whichever is needed to prevent a change in friction). For example, surfaces which are continuously in contact are less prone to form friction reducing surfaces than interrupted surfaces. Higher loads also prevent oxide buildup as do softer metals.

Very little is known of the wear behavior of materials at high temperatures; however, the wear rate is inversely proportional to hardness. Thus the wear would gradually increase as the temperature increases and become very high as the melting point is approached. For this reason either high melting point materials or low surface temperatures are desirable.

Applying these principles to brake materials, however, is not a simple exercise. For economic purposes copper or iron base materials are usually used. Many materials could be suggested which would retain their strengths and oxidation resistance to higher temperatures (Ni, Cb, Mo, to name a few) but at a much higher cost. With iron and copper, additives such as silica are added to prevent metal transfer. It is reasonable to assume that these might not be needed with other materials, however this would offer no substantial savings. The new materials may, however, offer more wear resistance and therefore ultimately be more economical. From the point of view of oxide stability the nickel-cobalt-molybdenum systems are also attractive. It is known that the reason that these metals can be used over the wide temperature range is that they form oxides which do not spall from the surface. Of particular interest is the Ni-Mo system which is known to form soft oxides which can be particularly beneficial in sliding applications.

Thus it can be seen that several schemes can be suggested for new materials or additives which would yield stabler friction values. It is, however, first necessary to understand the frictional behavior of the current materials to see if they are deficient in this regard.

Accordingly, as a first step, friction temperature studies were conducted with current materials. From these results, suggestions can be made for improved frictional behavior and material development approaches directed toward needed goals.

3.2 Dissipation of Frictional Heat

There are many reports of high temperatures in aircraft brakes but actual data in the literature is lacking. It is generally concluded, however, that surface temperatures can reach 800°C to 1000°C. Thermocouples embedded in the lining have recorded temperatures to 870°C. Disk temperatures after a plane has stopped have been measured at 650°C. Thermocouples mounted on the back of the end plates on the 747 reach 500°C. Whatever the actual temperature it is clear that any means which can be used to reduce it would be desirable. High surface temperatures cause high wear, extreme reductions in friction, and thermal stress at the surface. To obtain a cursory understanding

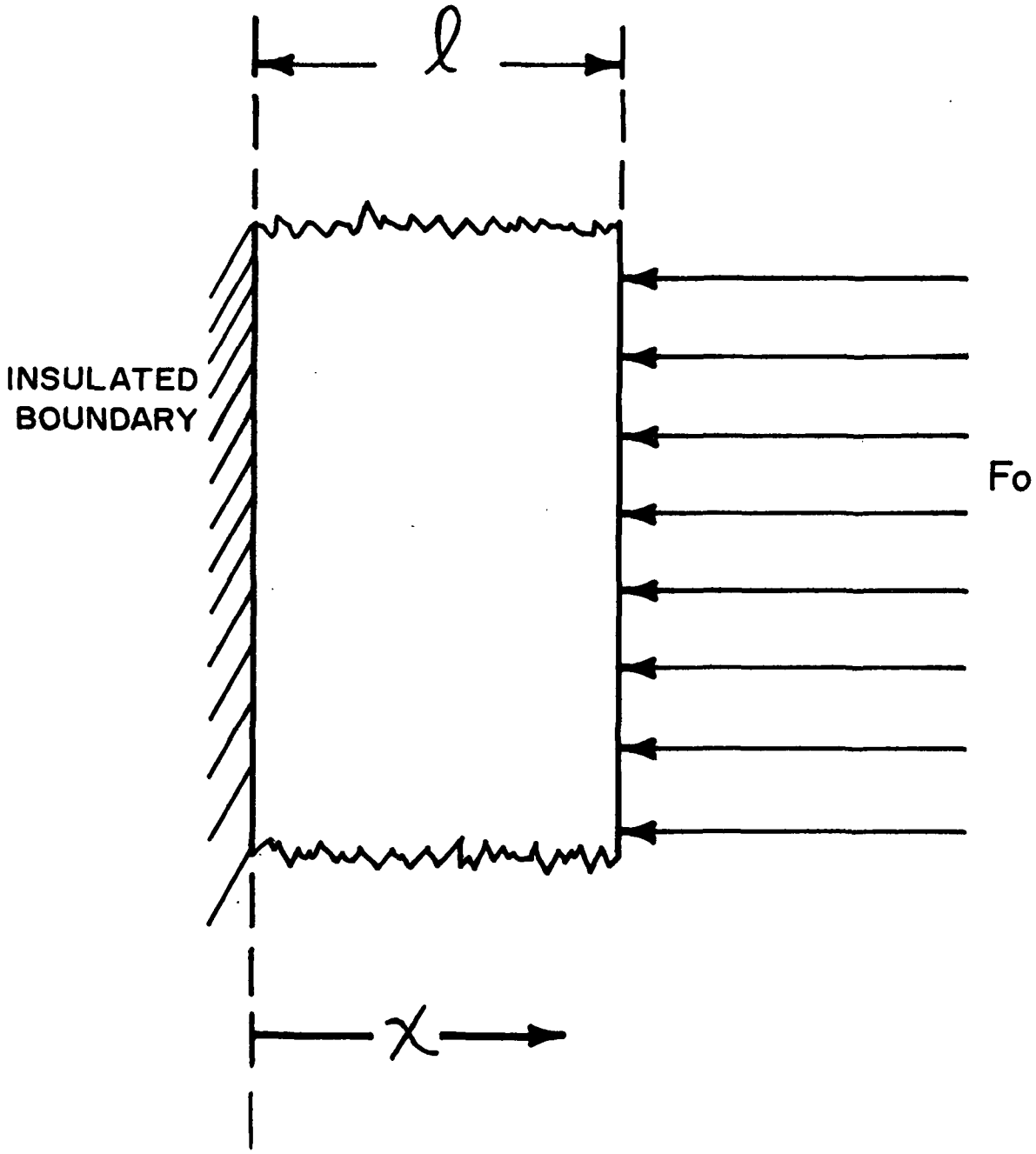


Figure 3. One Dimensional Heat Flow Model

of the variables involved one can consider separately the effects of the different variables using a model where heat flows only in one direction (Ref.3). A more precise analysis is presently being developed (Ref.4).

Consider the model of Figure 3. This represents the cross section of the rotor disk. A portion of the heat generated at the pad-rotor interface (F_0) flows into the disk. The center of the disk at x = 0 can be considered insulated since equal heat flows into each half disk. The surface temperature at x = ℓ for this condition is known to be (Ref.5):

$$T_S = \frac{LfV}{JA}\left(\frac{\ell}{k}\right)\left(\frac{\alpha t}{\ell^2}\right)^{\frac{1}{2}} G\left(\frac{\alpha t}{\ell^2}\right)^{\frac{1}{2}} \tag{1}$$

$$G\left(\frac{\alpha t}{\ell^2}\right)^{\frac{1}{2}} = \sum_{n=0}^{\infty} 2\ \text{ierfc}\left\{\frac{n}{\left(\frac{\alpha t}{\ell^2}\right)^{\frac{1}{2}}}\right\} + 2\ \text{ierfc}\left\{\frac{n+1}{\left(\frac{\alpha t}{\ell^2}\right)^{\frac{1}{2}}}\right\}$$

$$= 1.13 + 4\sum_{n=1}^{\infty} \text{ierfc}\ \frac{n}{\left(\frac{\alpha t}{\ell^2}\right)^{\frac{1}{2}}}$$

where

f = friction coefficient

c = specific heat

ρ = density

k = conductivity

α = diffusivity

erfcx = 1 - erfx

ierfc x = $1/\sqrt{\pi}\ e^{-x^3}$ - x erfc x

T_S = temperature rise

L = load

V = velocity

J = conversion constant

ℓ = thickness

t = time

A = area.

The function $G\left(\frac{\alpha t}{\ell^2}\right)^{\frac{1}{2}}$ has been evaluated for specific values of $\left(\frac{\alpha t}{\ell^2}\right)^{\frac{1}{2}}$ as shown below:

$\left(\frac{\alpha t}{\ell^2}\right)^{\frac{1}{2}}$	$G\left(\frac{\alpha t}{\ell^2}\right)^{\frac{1}{2}}$
.1	1.13
.5	1.13
.8	1.23
1	1.33
2	2.16
3	3.53
5	5.01
10	10.00

It can be seen that $G\left(\frac{\alpha t}{\ell^2}\right)^{\frac{1}{2}} \approx 1$ for $\left(\frac{\alpha t}{\ell^2}\right)^{\frac{1}{2}} < 1$ and $G\left(\frac{\alpha t}{\ell^2}\right)^{\frac{1}{2}} \approx \left(\frac{\alpha t}{\ell^2}\right)^{\frac{1}{2}}$ for $\left(\frac{\alpha t}{\ell^2}\right)^{\frac{1}{2}} > 1$. Therefore the temperature rise can be defined as:

$$T_S = \frac{LfV}{JA}\left(\frac{1}{kC\rho}\right)^{\frac{1}{2}} t^{\frac{1}{2}} \quad \text{for} \quad \left(\frac{\alpha t}{\ell^2}\right)^{\frac{1}{2}} \ll 1 \tag{2}$$

$$T_S = \frac{LfV}{JA}\,\frac{1}{\ell}\,\frac{1}{C\rho}\,t \qquad \text{for} \quad \left(\frac{\alpha t}{\ell^2}\right)^{\frac{1}{2}} > 1 \tag{3}$$

These equations are very similar to the equations which have been developed by Newcomb (Ref.6) for automobile brake bands. The difference in temperature at the end of the braking cycle predicted by Eq. 1 and Eqs. 2 and 3 combined is given in Figure 4 for typical braking conditions. It can be seen that the maximum deviation takes place when $\left(\frac{\alpha t_{max}}{\ell^2}\right)^{\frac{1}{2}} = 1$ where t_{max} is the time at the end of the braking cycle. Hereafter, this quantity, $\left(\frac{\alpha t_{max}}{\ell^2}\right)^{\frac{1}{2}}$, will be referred to as C^*. For maximum effort braking this difference amounts to 550°C, for normal braking 150°C. For $C^* > 2$ the equations give temperatures within approximately 100°C of each other. The exact equation always gives the higher temperature. Thus Eqs. 2 and 3 combined are probably sufficiently accurate for the normal braking process particularly when $C^* > 1$.

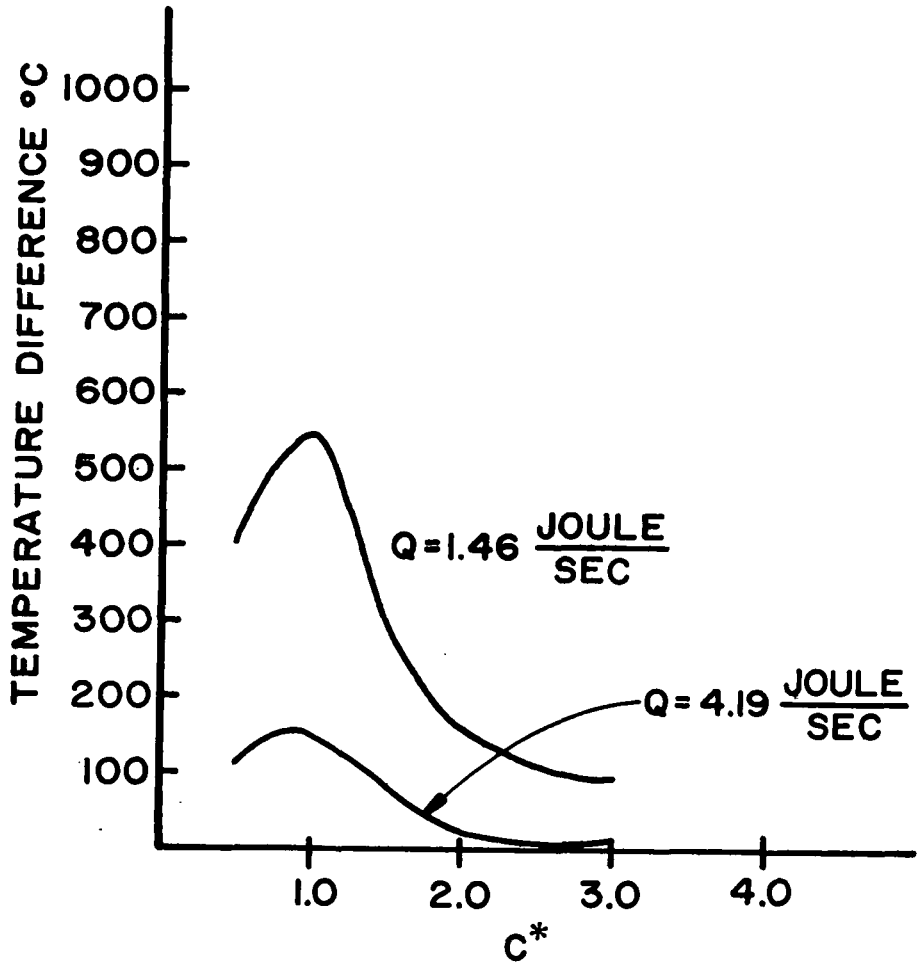


Figure 4. Effect of Changes in the Parameter $C^* = \left(\frac{\alpha t}{\ell^2}\right)^{\frac{1}{2}}$ on the Temperature Difference between the Exact and the Approximate Equations for Two Different Heat Inputs.

Since C^* for aircraft brakes is generally greater than unity, Eqs. 2 and 3 can be used to show the effects of the different parameters on surface temperatures. First of all, it can be shown that under identical conditions Eq. 2 gives higher values of T_S for $\left(\frac{\alpha t}{\ell^2}\right)^{\frac{1}{2}} < 1$. Equation 2 can be rewritten

$$T_{S(max)} = Q \frac{2\ell\rho}{W} \left(\frac{1}{kC\rho}\right)^{\frac{1}{2}} t_{max}^{\frac{1}{2}}$$

where t_{max} = time at the end of braking

$\ell > \alpha t_{max}$

W = weight

therefore

$$T_{S(max)} > Q \frac{2(\alpha t)^{\frac{1}{2}}}{W} \rho \left(\frac{1}{kC\rho}\right)^{\frac{1}{2}} t_{max}^{\frac{1}{2}}$$

$$T_{S(max)} \geq Q \frac{1}{2WC} t_{max}$$

$$T_{S(max)} \geq T_{S(max)}$$

as determined by Eq. 3. This means that to obtain the lowest surface temperatures C^* should be greater than 1 so that Eq. 3 will apply during the braking cycle rather than Eq. 2. Thus C^* may be used as a simple criterion for relating the material properties and the disk thickness. For each material with a given diffusivity, α, there will be a length ℓ such that $C^* = \left(\frac{\alpha t_{max}}{\ell^2}\right)^{\frac{1}{2}} > 1$. Furthermore based upon Eq. 3 the specific heat is seen to be the most significant parameter in determining the surface temperature; the material conductivity has little effect as long as $C^* > 1$.

For the actual brake conditions there is usually a weight or volume restriction which is imposed. Substituting either the weight, $W = 2A\ell\rho$, or the volume, $V = 2A\ell$, Eq. 3 reduces to:

$$T_S = 2 \frac{LfV}{J} \left(\frac{1}{W}\right) \left(\frac{1}{C}\right) t \qquad (4)$$

or

$$T_S = 2 \frac{LfV}{J} \left(\frac{1}{V}\right) \frac{1}{C\rho} t. \qquad (5)$$

Thus it is seen that if the area is held constant (Eq. 3) the surface temperature is dependent upon ℓ, C, and ρ. If the volume is held constant then the product of C and ρ is important and for constant weight only the specific heat is significant.

In order to demonstrate the significance of the different variables, some values of surface temperature were obtained using Eq. 1 and the following conditions:

$f = .25$

Load (for maximum effort stop) = 400 psi = 3×10^4 gs/cn^2

Load (for normal stop) = 125 psi = $.91 \times 10^4$ gs/cn^2

Stopping time = 25 sec

Average velocity = 840 cn/sec

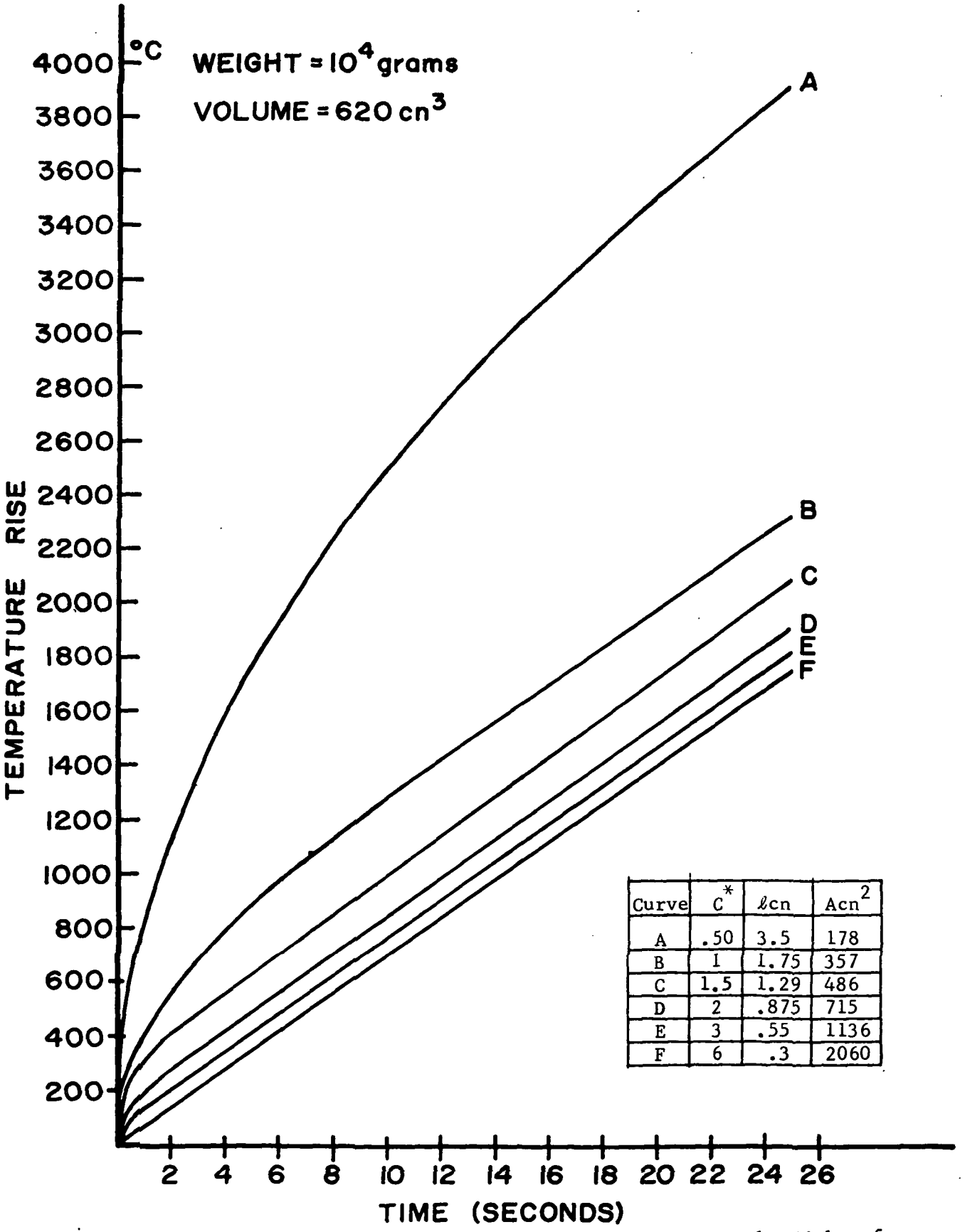
$$Q = \frac{1}{2} Q_{Total} = 14.6 \frac{\text{Joule}}{\text{sec}} = 3.5 \times 10^4 \text{ cal/sec maximum effort stop}$$

$$= 4.19 \frac{\text{Joule}}{\text{sec}} = 10^4 \text{ cal/sec normal stop.}$$

These conditions represent a constant deceleration. In actual practice, thrust reversal is initially used so the deceleration may be more rapid than linear. Thus the values obtained are higher than would normally be expected; however, the purpose here is to demonstrate the effects of changes in the variables rather than to determine the absolute values of surface temperature.

Figures 5 and 6 show the temperature rise as a function of time for different contact areas. In this example both the weight and the volume are held constant at 10^4 grams and 620 cn^3 respectively. Holding the weight and volume constant for the disk while the area increases means that the thickness (2ℓ) decreases as the area increases.

Figure 5 shows the temperature rise for the maximum effort stop using approximately the thermal properties for steel. $\left(\rho = 8 \frac{\text{grams}}{\text{cc}} ; C = .42 \frac{\text{Joule}}{\text{gram } ^\circ\text{C}}, k = .42 \frac{\text{Joule cn}}{\text{sec } ^\circ\text{C cn}^2} .\right)$



Curve	C*	ℓcn	Acn^2
A	.50	3.5	178
B	1	1.75	357
C	1.5	1.29	486
D	2	.875	715
E	3	.55	1136
F	6	.3	2060

Figure 5. Effect of Time on the Temperature Rise for Brake Disks of Different Thickness (2ℓ) and Area of Contact for the Maximum Energy Braking. Weight = 10^4 grams, Volume = 620 cn^3.

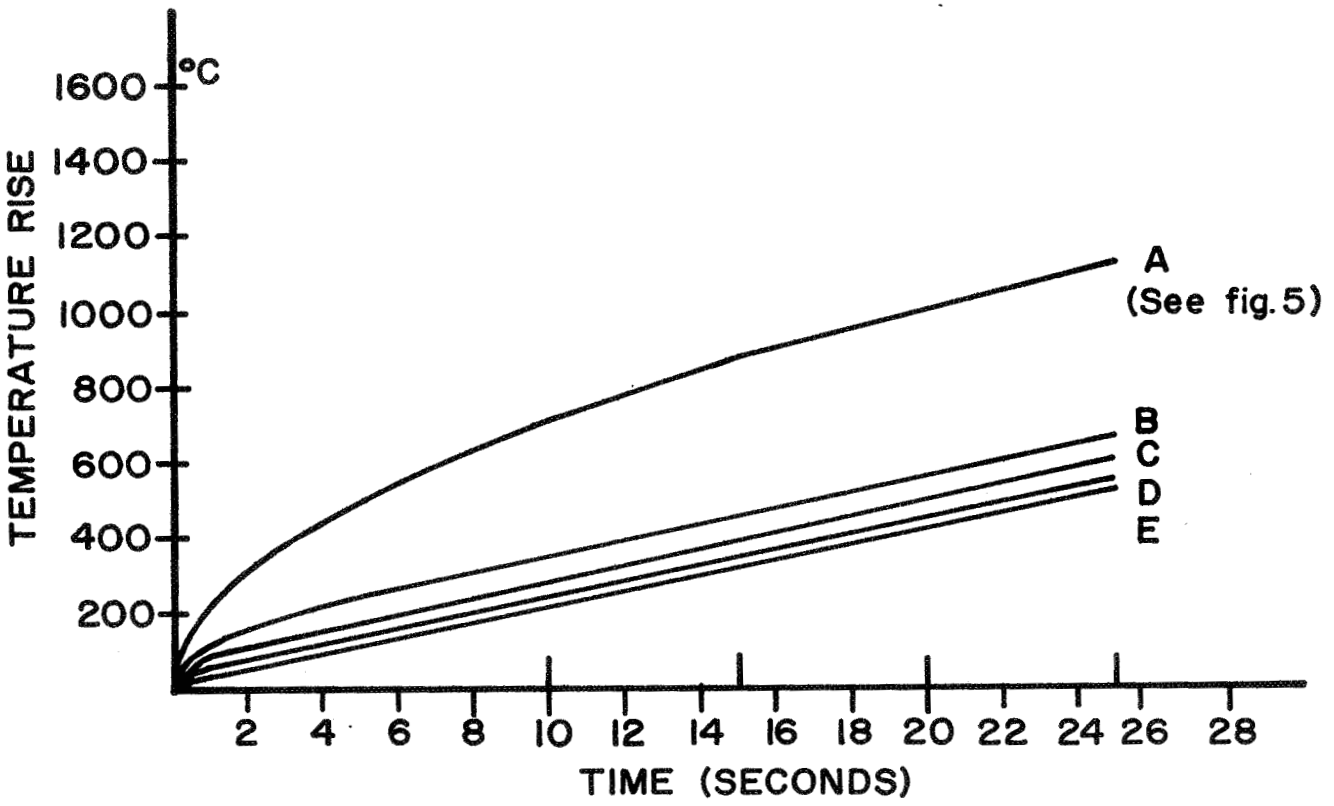


Figure 6. Effect of Time on the Temperature Rise for Brake Disks of Different Thickness (2ℓ) and Area of Contact for the Normal Energy Braking. Weight = 10^4 grams, Volume = 620 cn^3.

It can be seen that as A increases and ℓ decreases the temperature decreases. However, once C^* reaches a value of 1 further increases in area have much less effect. The same data for the normal braking stop is shown in Figure 6. The same trends are evident except the temperature differences are much smaller. This effect can also be seen by referring to Eq. 3. If the volume ($A \times \ell$) is constant, then a decrease in ℓ will bring about a corresponding increase in A and the temperature will remain constant.

In Figure 7 and 8 the temperature rise is plotted against time for two different areas ($A = 357$ cn^2; $A = 800$ cn^2) for the maximum effort stop. For these plots the thermal properties are the same as those used previously. Here, as in the previous figure, the thickness of the disk gets smaller, however in this case the area is held constant; in Figures 5 and 6 the area was allowed to increase so that the weight and volume remained constant. These data show that for $\ell > 1.75$ cn ($C^* > 1$) the temperature increases significantly for both contact areas. The larger contact area, of course, gives the lower temperature.

In Figure 9 the effect of changes in ℓ on surface temperature rise after 25 seconds is shown for the normal energy stops. Four different areas are shown: 357 cn^2, 600 cn^2, 800 cn^2 and 1136 cn^2. It can be seen that when ℓ decreases to values less than 1.75 cn^2 ($C^* > 1$) temperature begins to rise rapidly regardless of the contact area. This illustrates the significance of the criterion $C^* \approx 1$.

Figure 9 also shows the effect of wear on surface temperature rise. As wear takes place ℓ decreases and C^* increases. For a disk thickness of 1.2 cn and an area of 800 cn^2 (this is approximately the actual brake disk dimensions) the temperature rise is 660°C. Wear of .2 cn gives an added temperature rise of 140°C. This added temperature rise may be significant if the material will be damaged or the wear rate significantly increased at the resulting higher surface temperature of 800°C. If $C^* = 1$ then wear would have much less effect on surface temperature.

These previous results may be summarized as follows. If there are no restrictions on the size, weight, or area, then the optimum condition

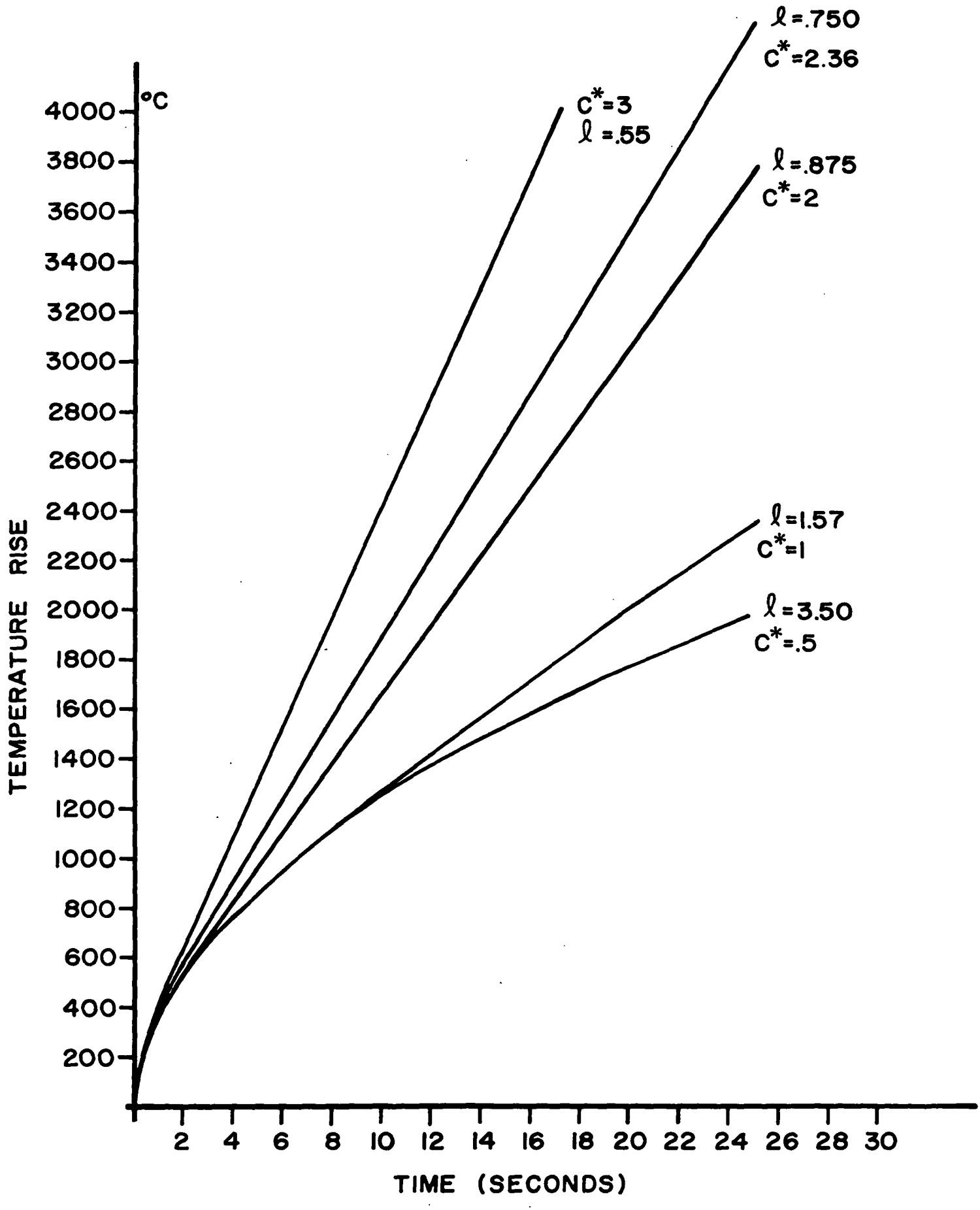


Figure 7. Effect of Time on the Surface Temperature Rise for Various Disk Thicknesses for Maximum Energy Braking. A = 357 cn^2.

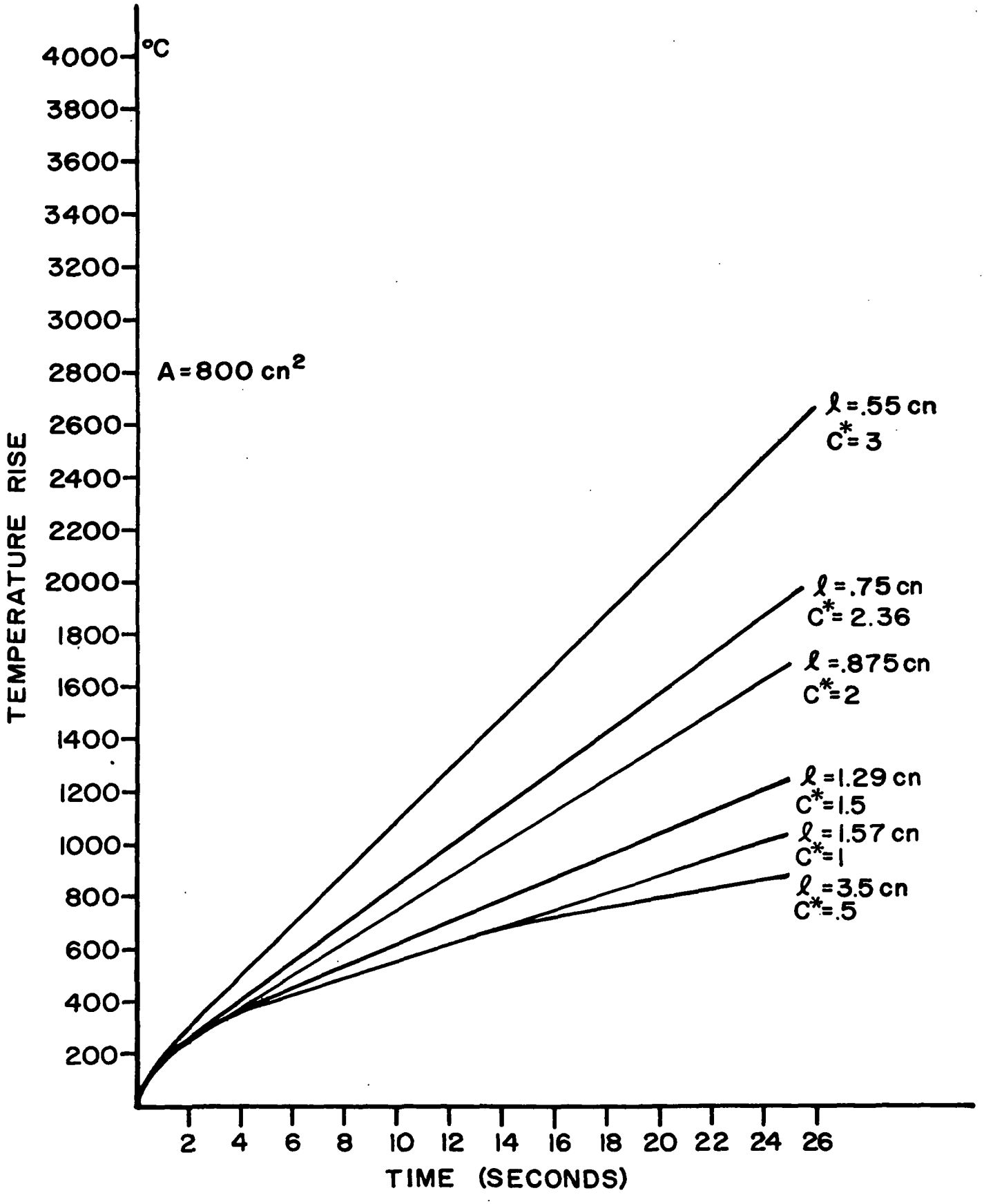


Figure 8. Effect of Time on the Surface Temperature Rise for Various Disk Thicknesses for Maximum Energy Braking. $A = 800\ cn^2$.

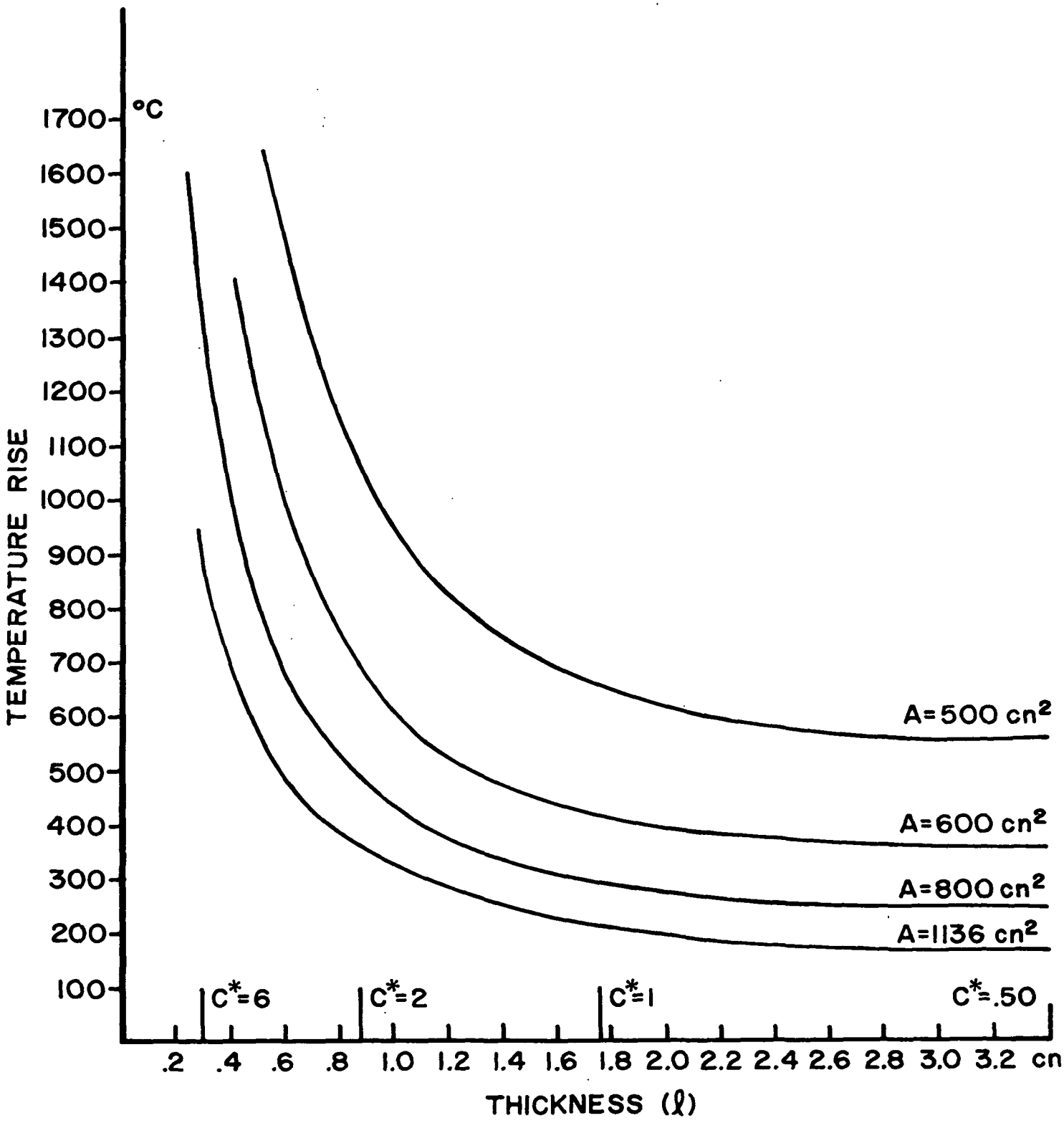


Figure 9. Effect of Disk Thickness (2ℓ) on the Surface Temperature Rise for Various Contact Areas for Normal Energy Braking

would be to make the brake disks as large as possible. However for aircraft brakes there are both size and weight restrictions so some compromises must be made. Under these conditions the previous data have shown that for a given material there is an optimum value of ℓ such that $\left(\frac{\alpha t_{max}}{\ell^2}\right)^{\frac{1}{2}} = C^*$ is approximately equal to 1 or slightly larger. If ℓ is greater than this value, excess weight is being carried which is not being effectively utilized. If ℓ is made smaller than this value then the area must be increased excessively to maintain the low temperature. If however there are no restrictions on the area (diameter) or the higher temperatures do not harm the material, smaller values of ℓ can be justified.

The previous discussion pertained to a given material. Changes in material will not only change the surface temperature but also values of C^*. If C^* is selected to be 1 or slightly greater then according to Eq. 3 the surface temperature will only be a function of the friction coefficient, the area of contact and the product of the specific heat and density. Under these conditions the thermal conductivity does not influence the surface temperature rise or the selection of brake materials. However, this is not precisely true. First of all, as shown in Figure 10, decreases in the conductivity decrease the value of C^* if the product $C\rho$ is held constant. If the conductivity decreases from a value of .42 as used in the previous calculation to a value of .042, then as shown in Figure 10, C^* will approach 1.0 and temperature will begin to rise. Actual calculations using Eq. 1 for the two values of heat generation are shown in Figure 11 for the two different conductivities. These data show approximately 140°C temperature rise for this conductivity change. Although this temperature rise is not large it would increase much more drastically if C^* decreased below values of unity. This may happen if there is sufficient oxidation of brake surfaces or interfaces. This point will be discussed later. A second factor to consider is that with low conductivity nonuniform temperature distribution within or along the surface of the brake disks (due to different surface velocities); these temperature variations may cause thermal distortions which will reduce the effective contact area. Accordingly, considerations of the thermal conductivity should not be neglected in the selection of brake materials.

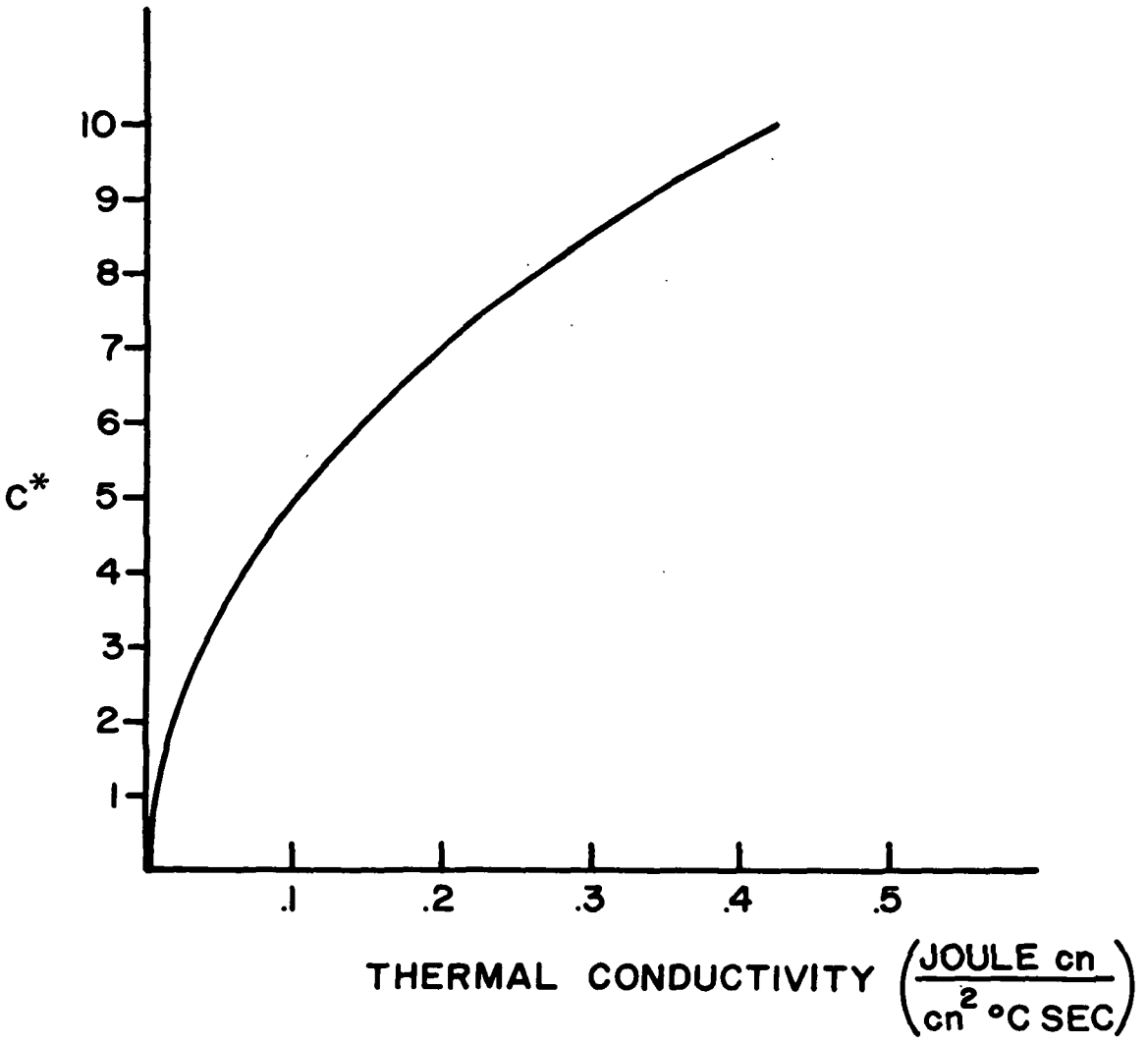


Figure 10. Effect of Thermal Conductivity on Values of C^* • ℓ = .55 cn

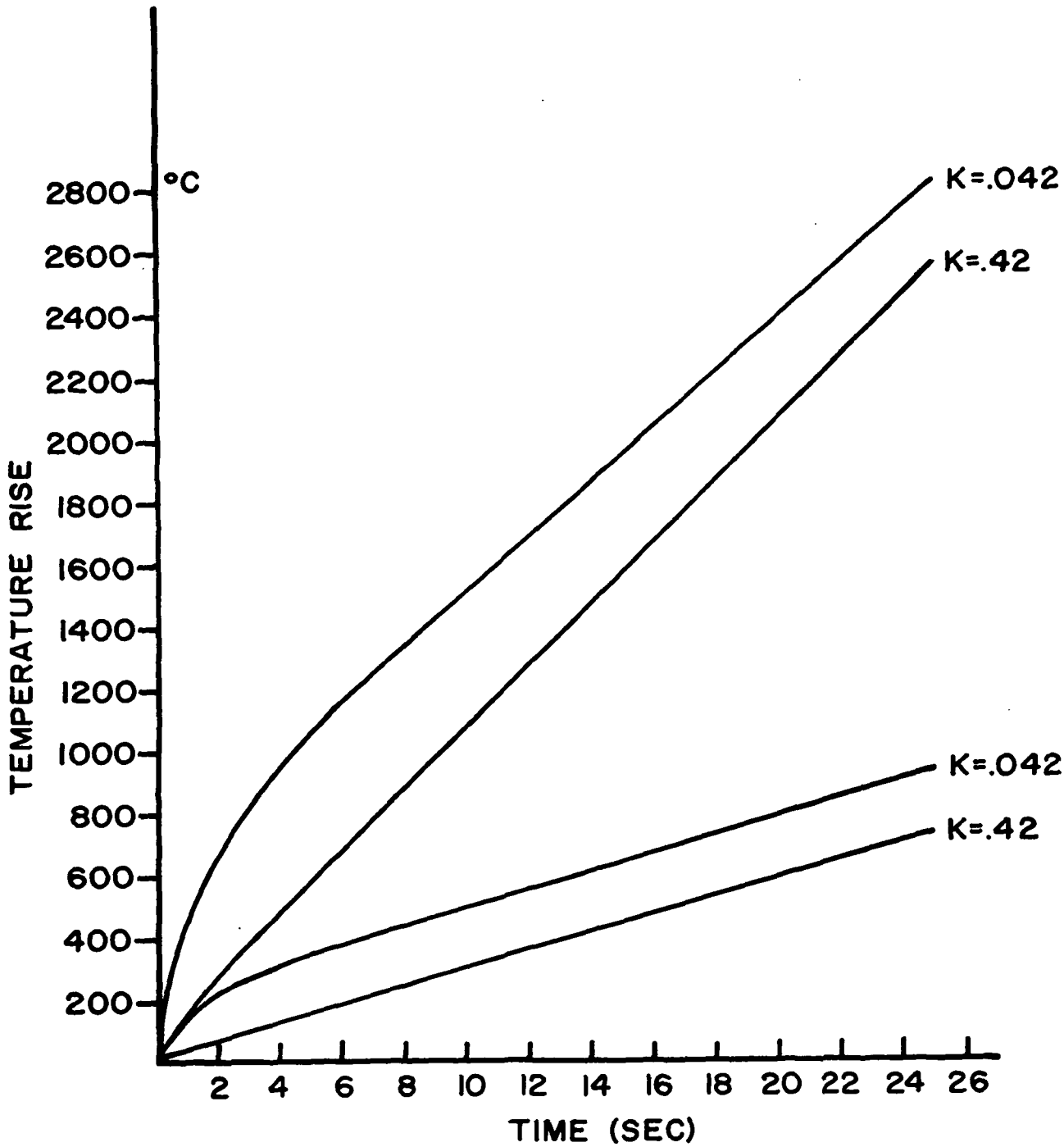


Figure 11. Effect of Time on the Surface Temperature Rise for Two Different Values of Thermal Conductivity $\left(\frac{\text{Joule cn}}{\text{cn}^2\text{sec }^\circ\text{C}}\right)$ both Maximum Energy Braking and Normal Energy Braking

Since surface temperature depends upon the friction coefficient, a low friction material might effectively serve as a brake material if some way could be found to obtain the same braking force at the surface. This is possible if the load is increased proportionately. The surface shear stress then remains constant; however, since the microscopic area of contact is a function of the load, the higher load would mean greater contact area, improved heat dissipation, and lower surface temperatures. The only unknown factor is the wear. The wear is generally considered to be directly proportional to load. Therefore, this may increase the wear. However, in high temperature operation, the wear is proportional to the surface temperature so it may be more significant to reduce the temperature than the load.

Changes in the contact area are also seen to play a significant role in determining the surface temperature either on the microscopic or the macroscopic scale.

On the microscopic scale the load is considered supported on asperities randomly distributed on the surface. There is an average contact area size $\bar{a}r$. As the load is increased $\bar{a}r$ remains essentially constant but the number of contacts increases due to the elastic or plastic deformation of the surface. Thus a low yield strength or a low modulus material will give a higher contact area at a given load than one with a high yield and modulus. However, some metals with modulus equal to or greater than copper alloys have much higher melting points (columbium and titanium alloys) and could be considered. Furthermore, low modulus materials give improved abrasive wear resistance.

On the macroscopic scale the contact area can be reduced due to two different effects: thermal distortions and the Barber effect. Thermal distortions due to nonuniform differential thermal expansion can result in isolated contact areas. More important, Barber (Ref.7) has made the significant observations that the position of contact is not constant but is continually shifting from one point to another. The process is described as follows: Sliding starts at one point within the contact area. This point heats up, expands, and carries a greater portion of the load. This process continues until the surface temperature reaches the level where

excessive wear occurs. The point of contact then shifts and the process begins again. Under such a condition the total heat inputs are the same as if the entire macroscopic area were in continuous contact; however, extremely high surface temperatures are generated due to the smaller contact areas. To minimize this effect they suggest low thermal expansion materials and a resilient mounting. A low modulus material can have a similar effect.

3.3 Used Pad Examination

In order to determine the significance of the oxide film and other factors some used brake pads and their mating steel disks were collected at random from the airlines and military. They were pads that had been discarded during overhaul of the brake. Thus they represent the worst condition of service. The pads were of the metallic variety only and consisted of the sintered metal contained in a steel jacket. They were all copper base materials. The pad shapes were either round or trapezoid. The pads and the steel disks were cut up and examined* as follows:

Surface condition
Metallographic study of cross sections
Hardness of the rotor disks.

These are discussed separately.

3.3.1 Surface Condition

The used and discarded pads were, on the average, .200 to .312 cn thick. The wear was generally uniform except that the center path from front to rear was worn more than either the outer or inner diameter path (Figure 12). This high wear path corresponded to the width of the center hole where a rivet was used to hold the pad to its backing plate. The difference in wear was about .025 cn.

---

* This work was performed by Mr. S.J. Calabrese of Mechanical Technology, Inc.

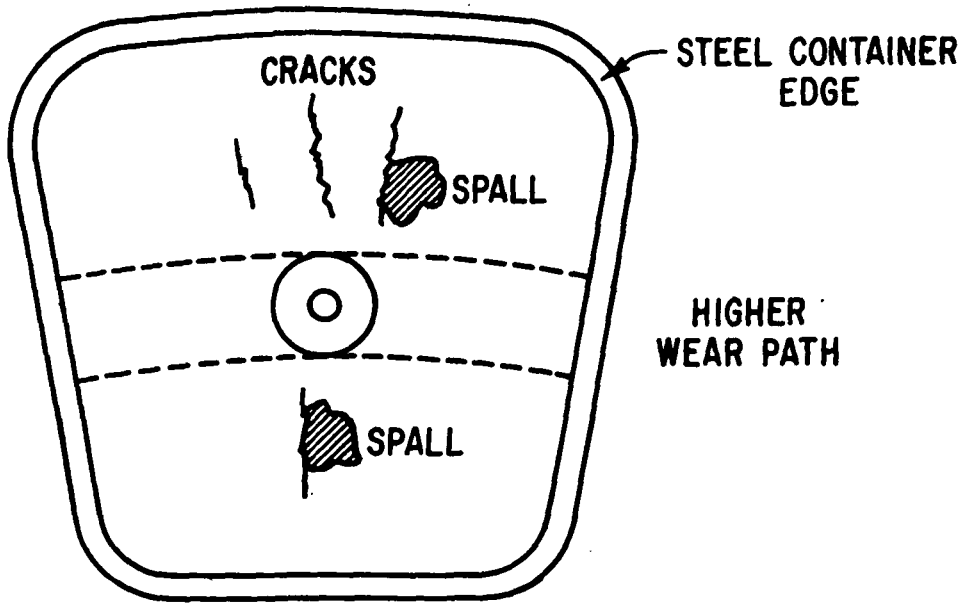


Figure 12. Worn Brake Pad Surface which Shows Cracking Pattern Seen on Slightly Worn Pads.

All surfaces (pad and disk) were completely covered with oxide. In most cases material had spalled from the surface so the complete area was not in contact. In many cases as much as 75% of the surface had spalled away and it appeared as if sliding was predominately on the steel container edge. Where the surface had no spalling there were center hair line cracks as shown in Figure 12. Many examples were found where the initial spalls started at these cracks.

The steel disks are also oxidized and had a high spot at the center of the sliding path which corresponds with the high wear path on the pad. The sliding surfaces are covered with oxide. It is not uniform but appears to be smeared across the surface. Very small radial cracks are often seen and the edges may also be cracked.

3.3.2 Metallographic Study of Cross Section

Fourteen pads from various sources were sectioned, mounted, and polished. The unused pad is shown in Figure 13 and representative used pads in Figure 14. From examination of these specimens at different magnifications certain conclusions were drawn. These are described in the following paragraphs.

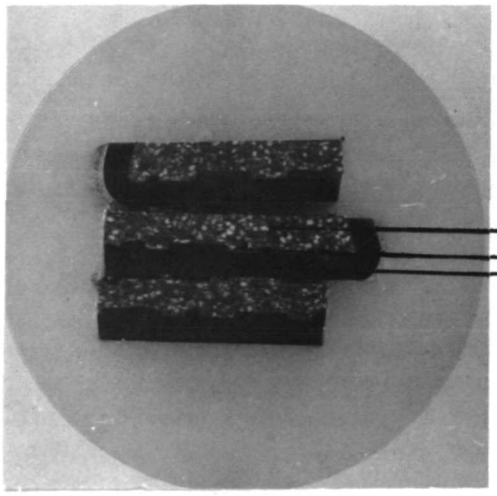
First of all, it was found that the oxide film at the surface of the sliding interfaces was very thin. As shown in Table 1 the film thickness varied from .0003 to .0005 cn. This thickness would have little influence on surface temperatures. However, there was oxide dispersed throughout the pad material. There was also oxide surrounding each individual particle in the matrix; the steel mesh (located between the sintered material and the steel container) was heavily oxidized on all surfaces; and the steel container was oxidized on both the inside and outside.

Figure 15 shows photomicrographs of the typical pads. All of the products are identified. The light particles are copper. Around each light particle can be seen a grey film which is presumed to be copper oxide. No such film is seen in the unused pads, Figure 16.

TABLE 1

MEASUREMENT OF OXIDE FILM THICKNESS ON USED BRAKE PADS

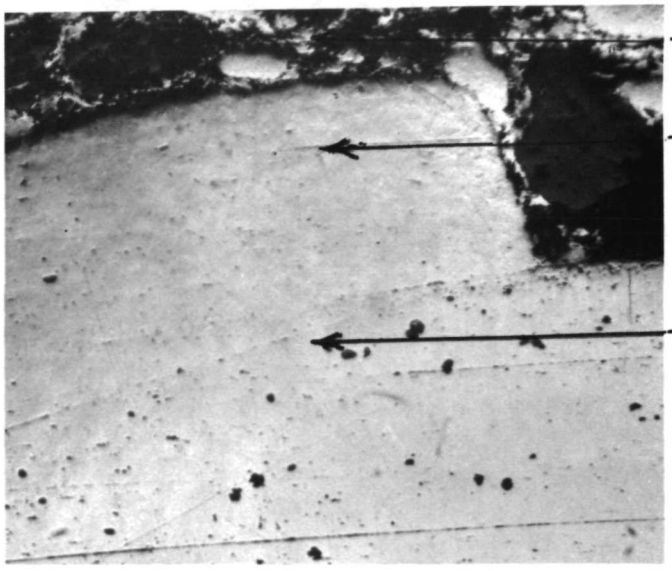
Pad	Thickness (cn) Back of Pad	Thickness (cn) Inside of Container	Thickness (cn) Mesh	Thickness (cn) Surface
1	.0019	.0013	.0025	.0003
2	.0025	.0003	.0025	.0003
3	.0050	-	.0025	.0005
4	.0025	.0020	-	-
5	.0025	-	.0013	.0003
6	.0063	.0025	-	-
7	.0025	.0025	.0013	.0003
8	.0025	.0025	.0013	.0003
9	.0025	.0025	.0003	.0005
10	.0025	.0038	.0025	.0003
11	.0038	.0038	.0018	.0005
12	.0050	.0038	.0020	.0005
13	.0050	.0025	.0020	.0005
14	.0050	.0025	.0003	.0005
AVE	.0035	.0025	.0017	.0004



A - Friction compound ($Cu + Al_2O_3$).

B - Steel mesh.

C - Cu coated steel backing.



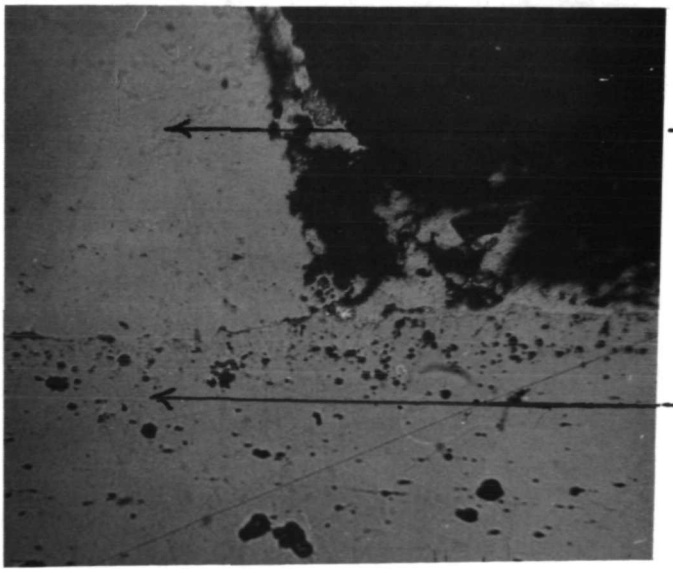
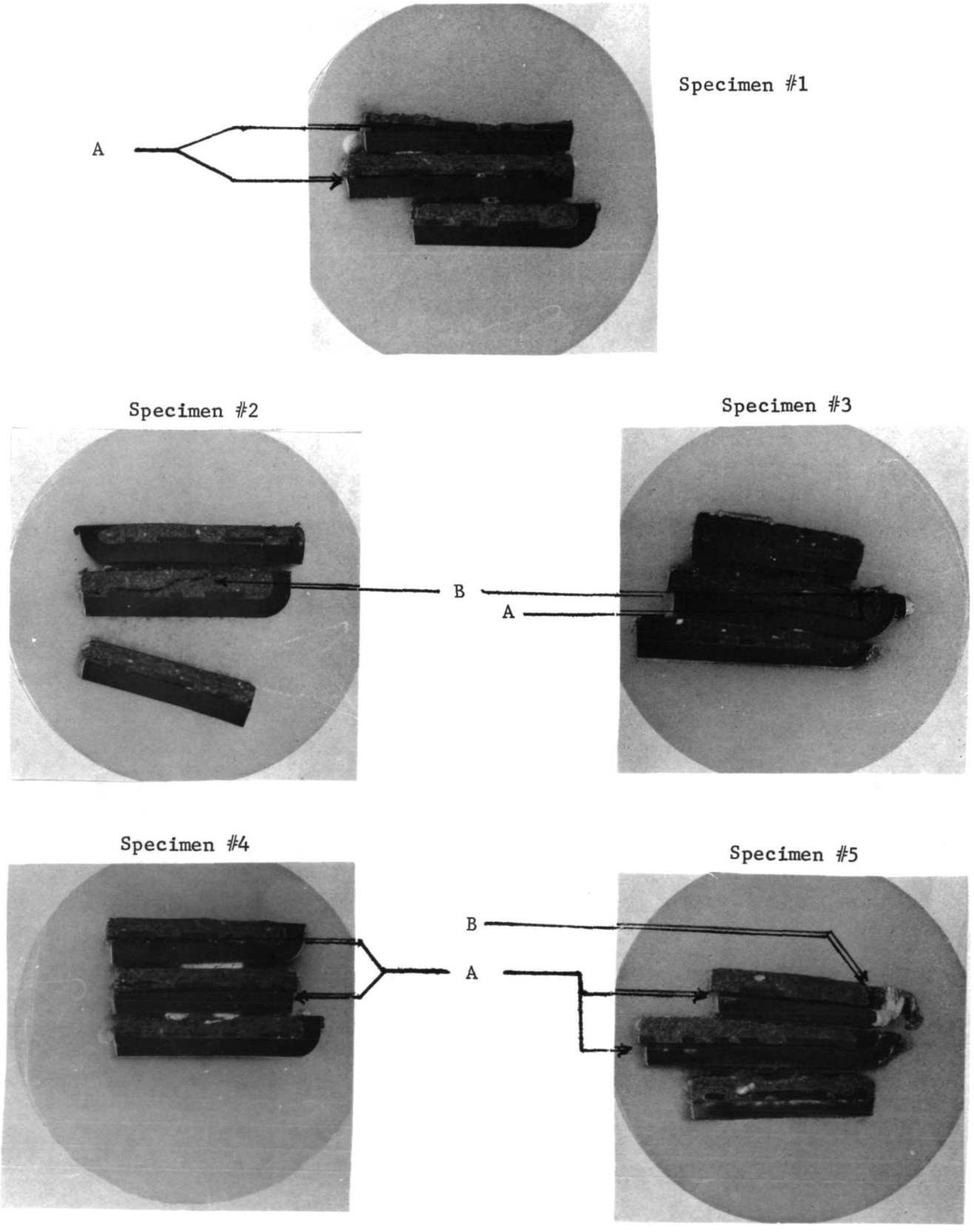


Figure 13. Unused Brake Pad Showing Intimate Contact Between the Friction Compound, Steel Mesh and Steel Backing

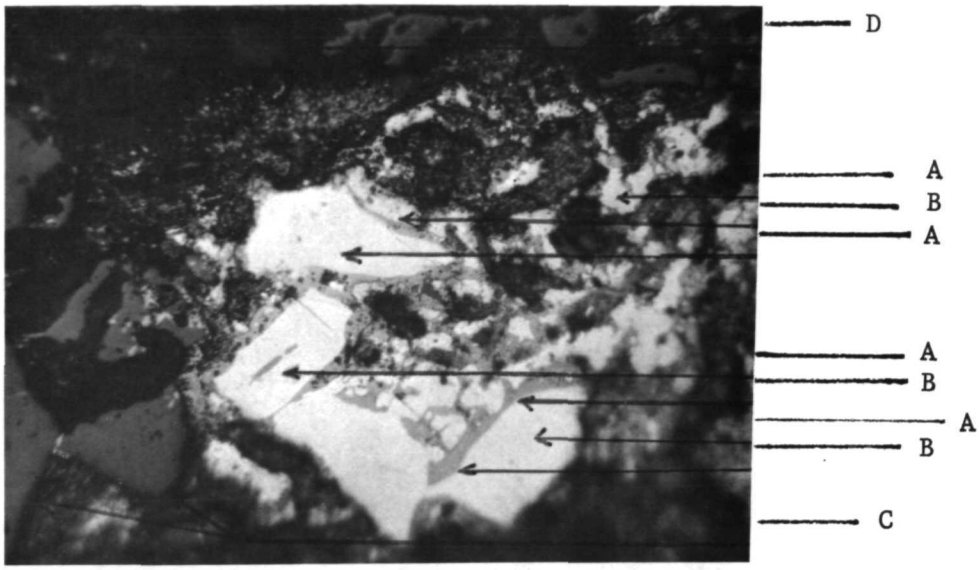


A - Separation of steel mesh from backing.

B - Cracked area through the friction compound.

Figure 14. Cross Sectioned Specimens of Five Worn Brake Pads

200 X mag.



A - White--metallic particles (Cu) found in friction compound.

B - Oxides--grey. Oxidation products found in friction compound.

C - Oxides--grey. Large particles sintered with the Cu to produce friction compound.

D - Black--voids.

200X mag.

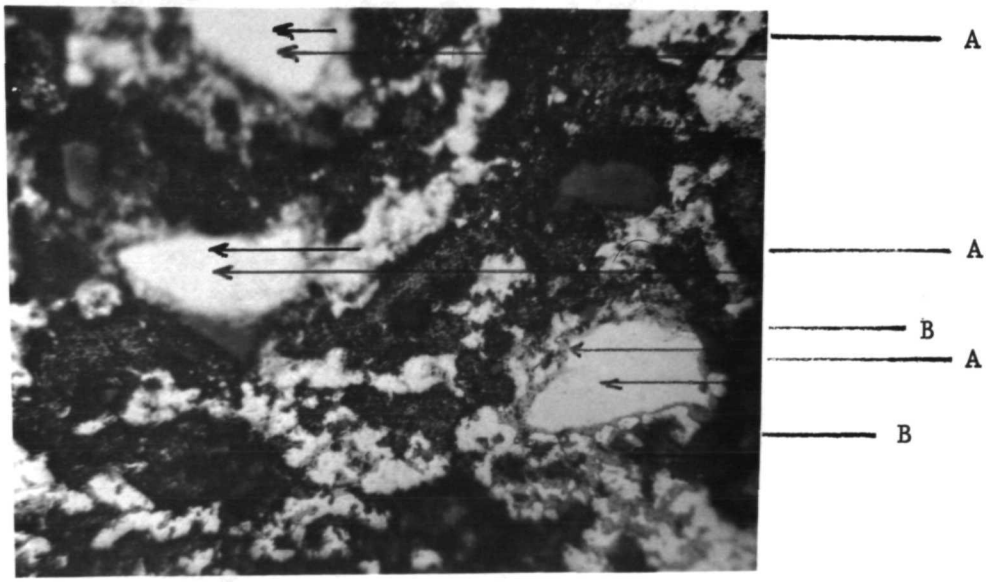
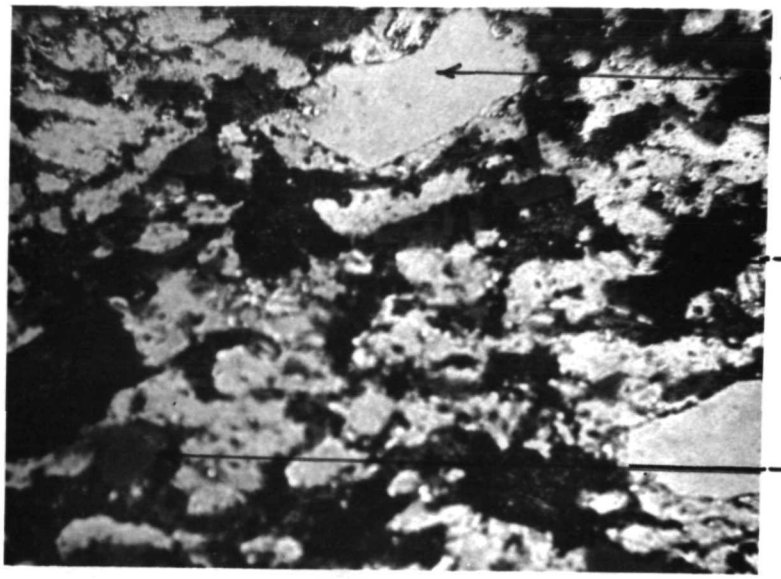


Figure 15. Typical Appearance of the Friction Compound Found on a Worn Brake Pad

250× mag.



250× mag.

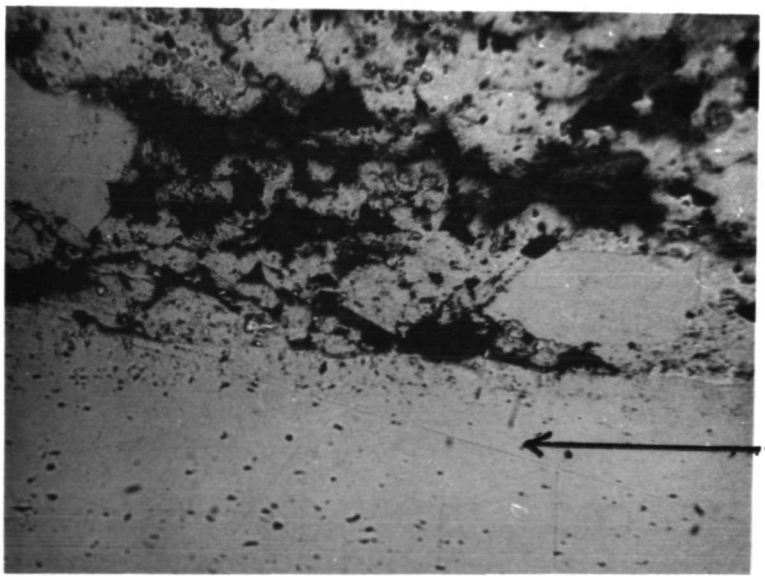
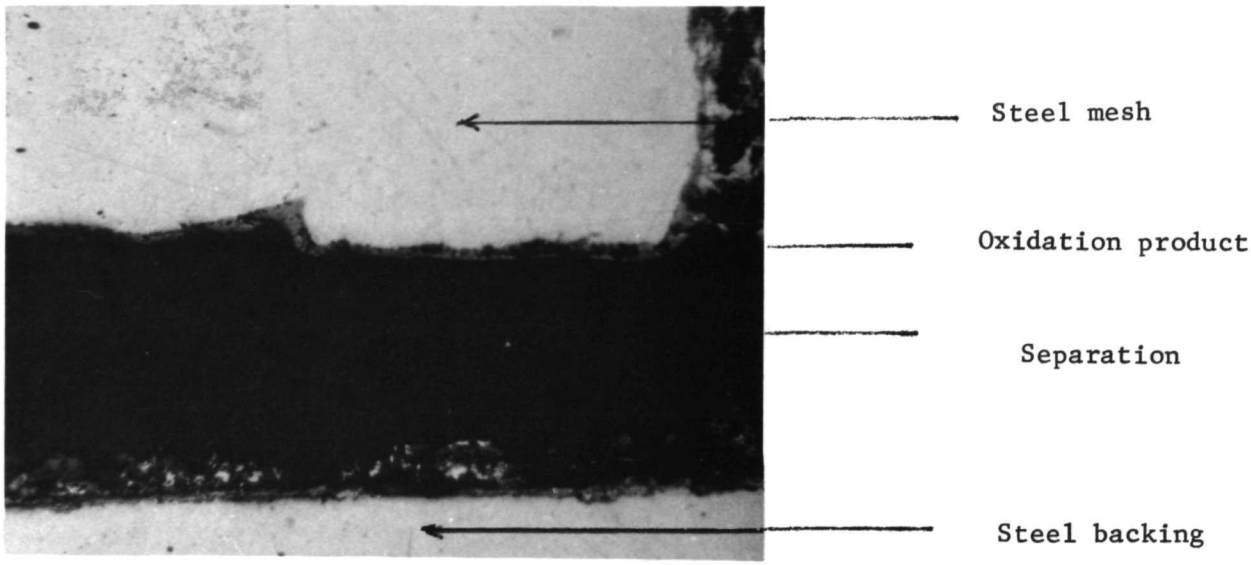


Figure 16. Unused Brake Pad Showing no Oxidation Coating on Metallic Particles (above) and Intimate Contact between Frictional Compound and Steel Backing (below)

100× mag.



250× mag.

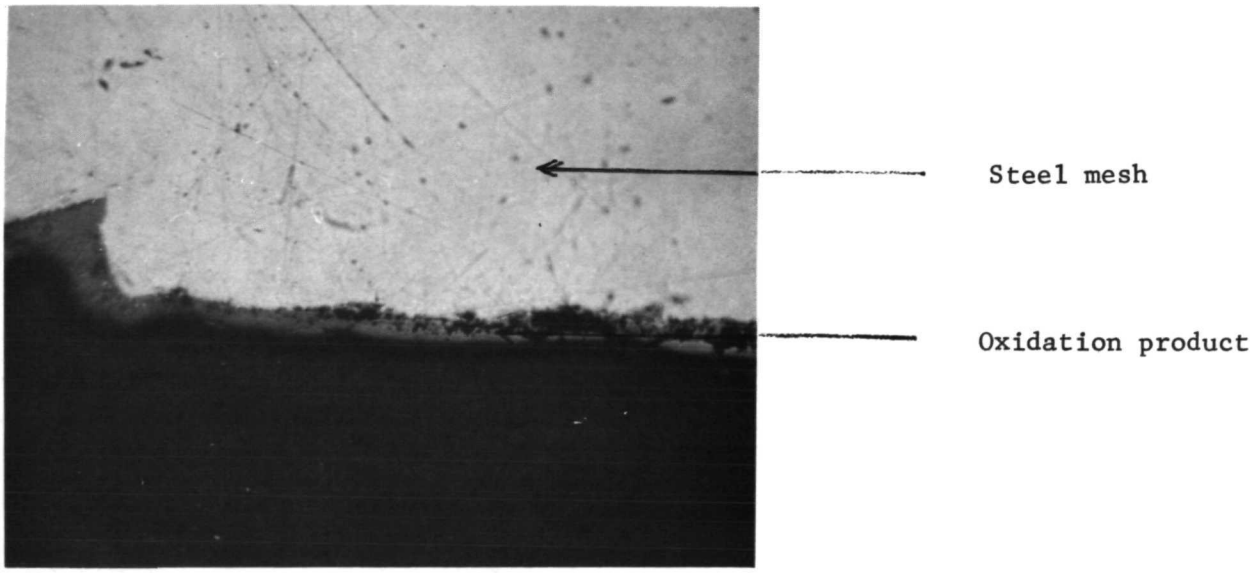


Figure 17. Photomicrographs of a Cross Section Pad Showing Separation between Steel Mesh and Backing Material

Figure 17 shows the photographs of the cross sections of five pads. The curved specimens are the edges and the straight portion is the center of the pad. Examination of the cross section showed several interesting points. First, it was seen that there was separation of the brake material from the steel container (marked A) and cracks in the material parallel to the surface (marked B). These air gaps could be very influential in preventing heat flow through the pad. The separation can occur between the mesh and the steel contained (Fig.17) or between the mesh and the friction material (Fig.18), or between different parts of the matrix (Specimen 2, Fig.19). No such separation was seen in the new pads (Fig.13). This series of photographs also shows examples the oxide formed on both the back of the steel mesh and the inside of the steel container (Fig.17). Even if no separation occurs an oxide is visible on the inside of the steel container (Fig.18). An oxide film was also found on the outside back of the steel container. This is shown in Figure 19. The thickness of these oxide films was measured; these data are shown in Table 1.

It can be seen that the oxide films on the back of the pad varied from .0019 to .0063 cn; the thickness on the inside of the container from .0003 to .0038 cn and on the mesh from .0003 to .0025 cn. Thus the total thickness of oxide is .0025 to .0126 cn. It is of interest to determine what effect this thickness of oxide might have on the surface temperature and on the value of C^* since the results of Reference 8 show that very thin surface films can have a major effect on surface temperature.

If, as previously discussed, $C^* > 1$ then Eq. 3 would apply and there would be little or no effect of oxide on the surface temperature. If however this amount of oxide can reduce C^* so that $C^* < 1$, then this amount of oxide would be important. Using the values of the thermal properties of brake materials one obtains a value of $C^* = 4.3$. Assuming a linear law of mixtures, .0126 cn film thickness of oxide from a total thickness of .312 cn would only reduce the average conductivity from .011 to .0095 $\frac{\text{Joule cn}}{\text{sec cn}^2\ ^\circ\text{C}}$. This of course would not reduce C^* significantly. Thus, based upon these considerations, this amount of oxide is not significant. However, to be sure it would be necessary to make actual thermal conductivity measurements of the used brake pads.

100× mag.

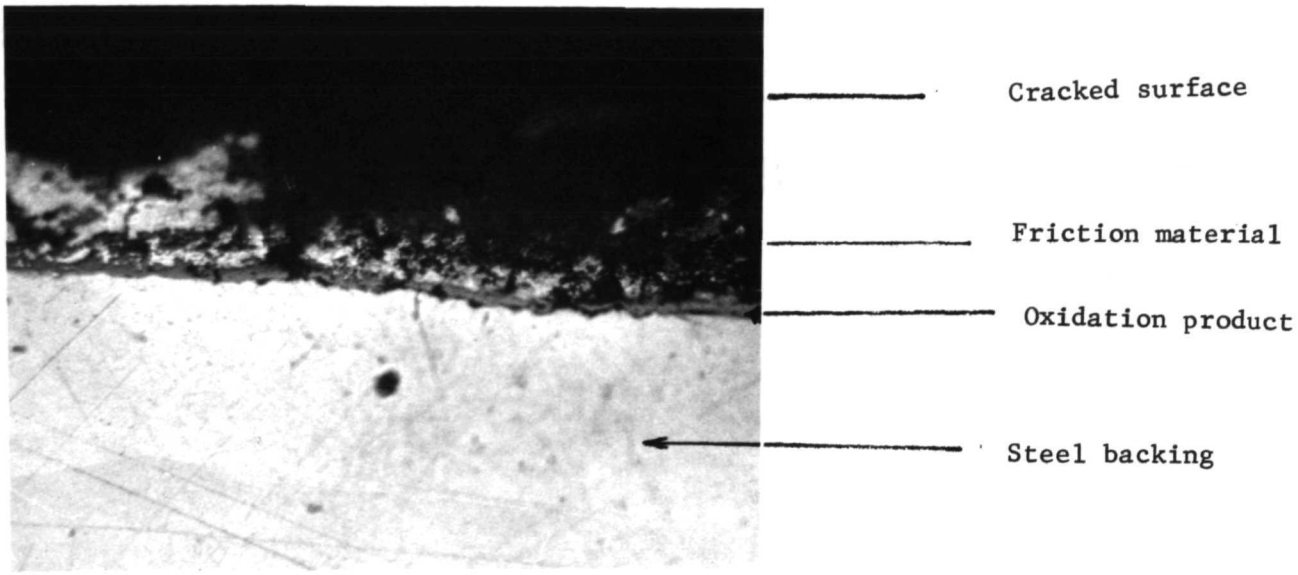


Figure 18. Photomicrograph of Pad Showing Separation through the Friction Compound

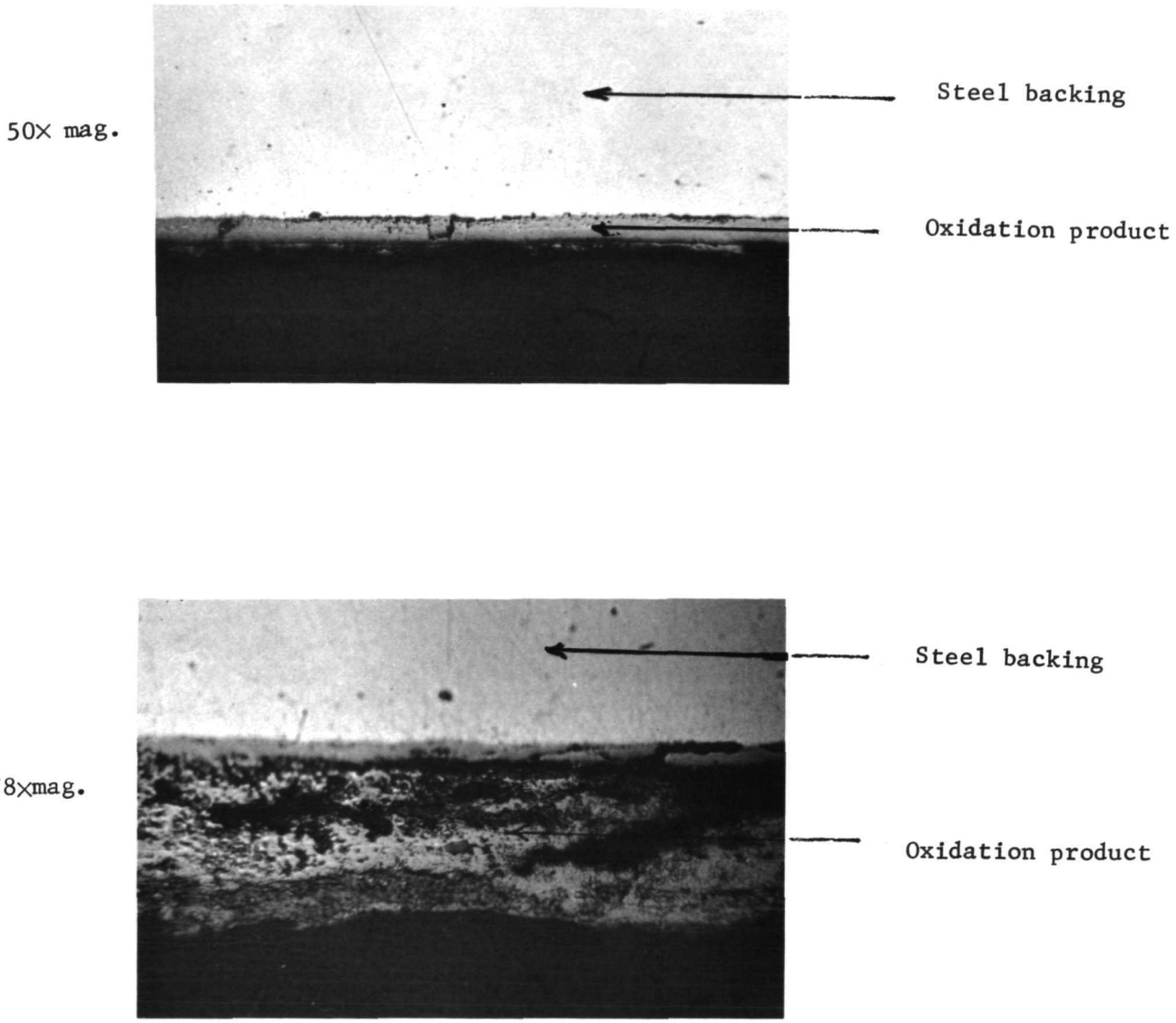


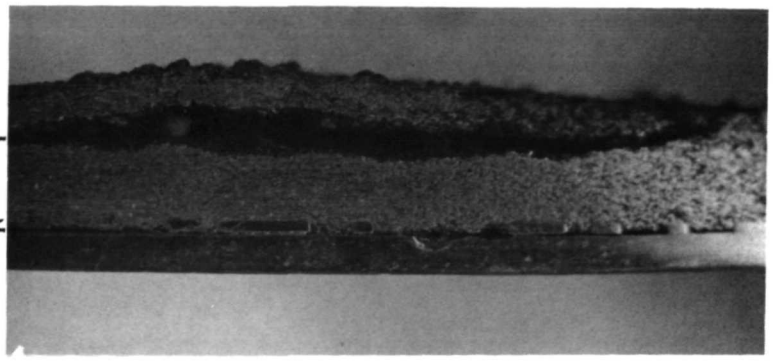
Figure 19. Oxidation Product Seen on the Back of a Worn Brake Pad

The observed separations are of course another matter. The conductivity of air is .00001 in the S1 system. Transfer of heat would have to be by convection or radiation. However, these cracks undoubtedly close during the braking cycle and would accordingly have only a minor effect on surface temperatures.

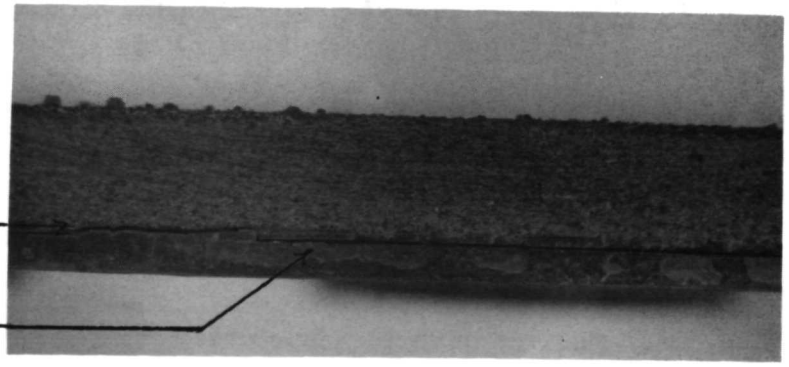
The spalling of the surface and initial cracking shown in Figure 12 are clearly the consequences of the cracking and separation shown in cross section. It can be hypothesized that this cracking is the result of the differential thermal expansion between the copper brake material and the steel container. The brake material is also much hotter than the container since the container is further from the surface. Then the brake material tries to expand and is restrained. The resulting compressive forces cause the material to bulge and crack at the center when the brake is released. Repeated applications of this process (now at higher temperatures due to the cracking) will eventually cause the material to spall.

In an attempt to reproduce cracking due to surface heating, an unused brake pad was cut in half and heated at the surface. The pad was placed on a large piece of aluminum to produce a heat sink. The surface temperature was monitored by means of a thermocouple in contact with the surface. The cross section of the pad was examined before heating to insure that the pad was sound with no separation between the friction compound, the steel mesh and the steel backing. The surface was heated to between 650°C and 760°C for one minute. The first half bulged and cracked through the friction compound. A similar test was performed on the second half of the brake pad. This time the temperature was held below 680°C for one minute. This test produced a failure by separating at the steel mesh areas. Figure 20 shows the results of these tests. The upper photograph shows the specimen which had been heated to between 650°C and 760°C. The lower photograph shows the cross section of the specimen which had been heated to below 680°C. Note that in both cases, separation had taken place at the steel backing.

If the surface temperature at the sliding interface does indeed reach temperatures in excess of 650°C, severe oxidation would take place on the steel disk. Since the disk is in contact with the wear surfaces, the



2.5× mag.



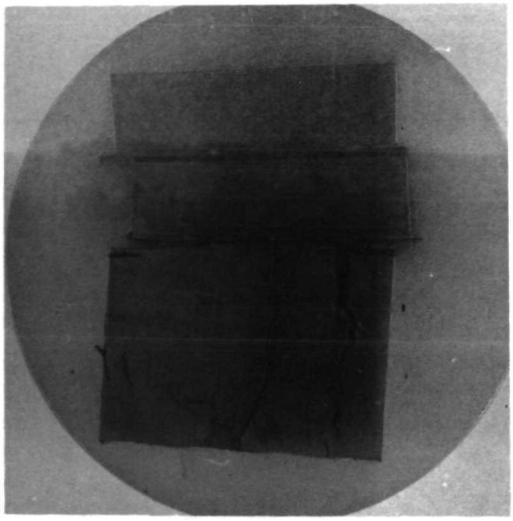
2.5× mag.

A - Cracked Area through the Friction Compound

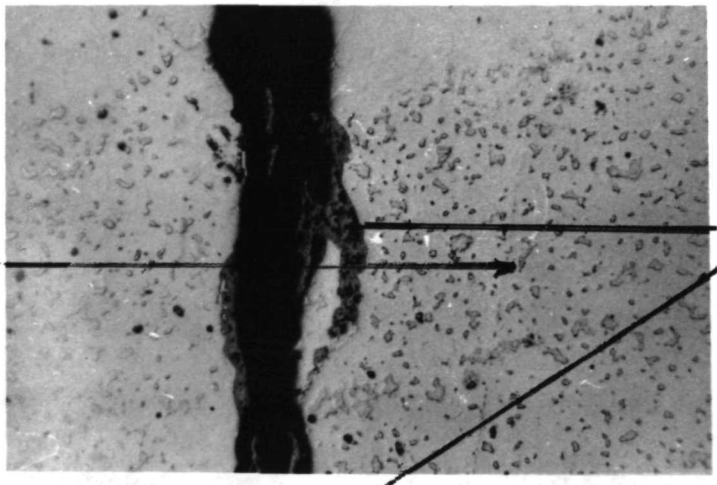
B - Separation of Friction Compound from Steel Mesh

C - Separation of Steel Mesh from Steel Backing

Figure 20. Specimen after Surface Heating Test.
Upper specimen heated to between 650°C and 760°C for 60 sec.
Lower specimen heated to below 650°C for 60 sec.



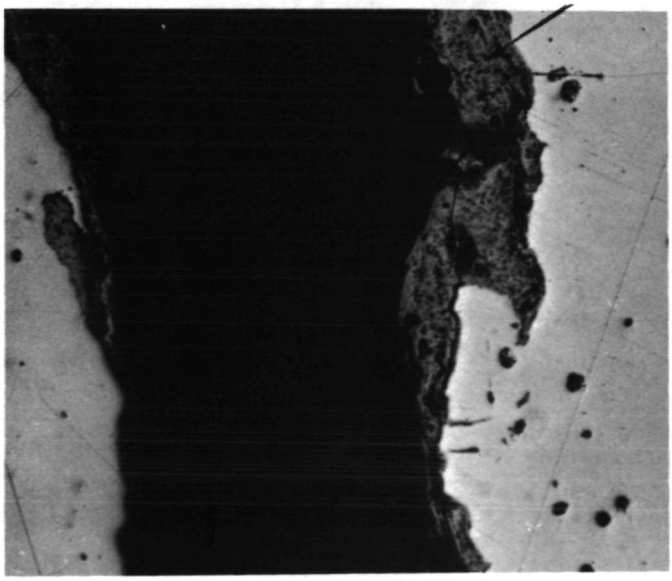
2.5× mag.

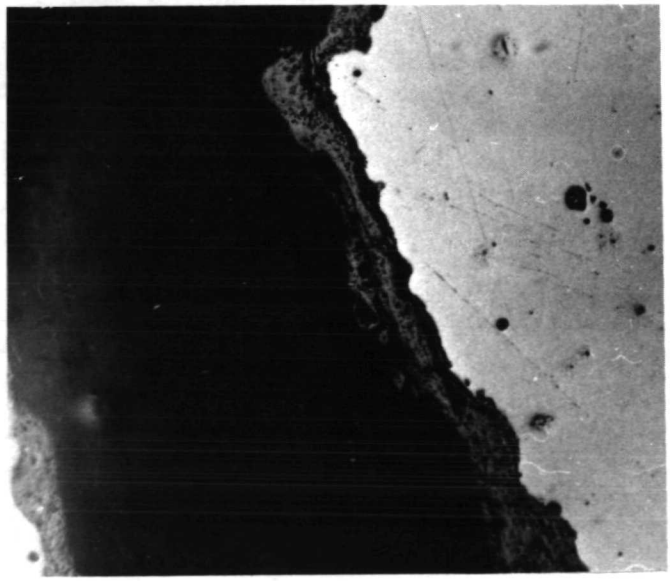


50×

Intermetallic compound precipitant area

Oxidation product on the walls of a crack





00× mag.

Figure 21. Cross Sectioned Photographs of Steel Disk

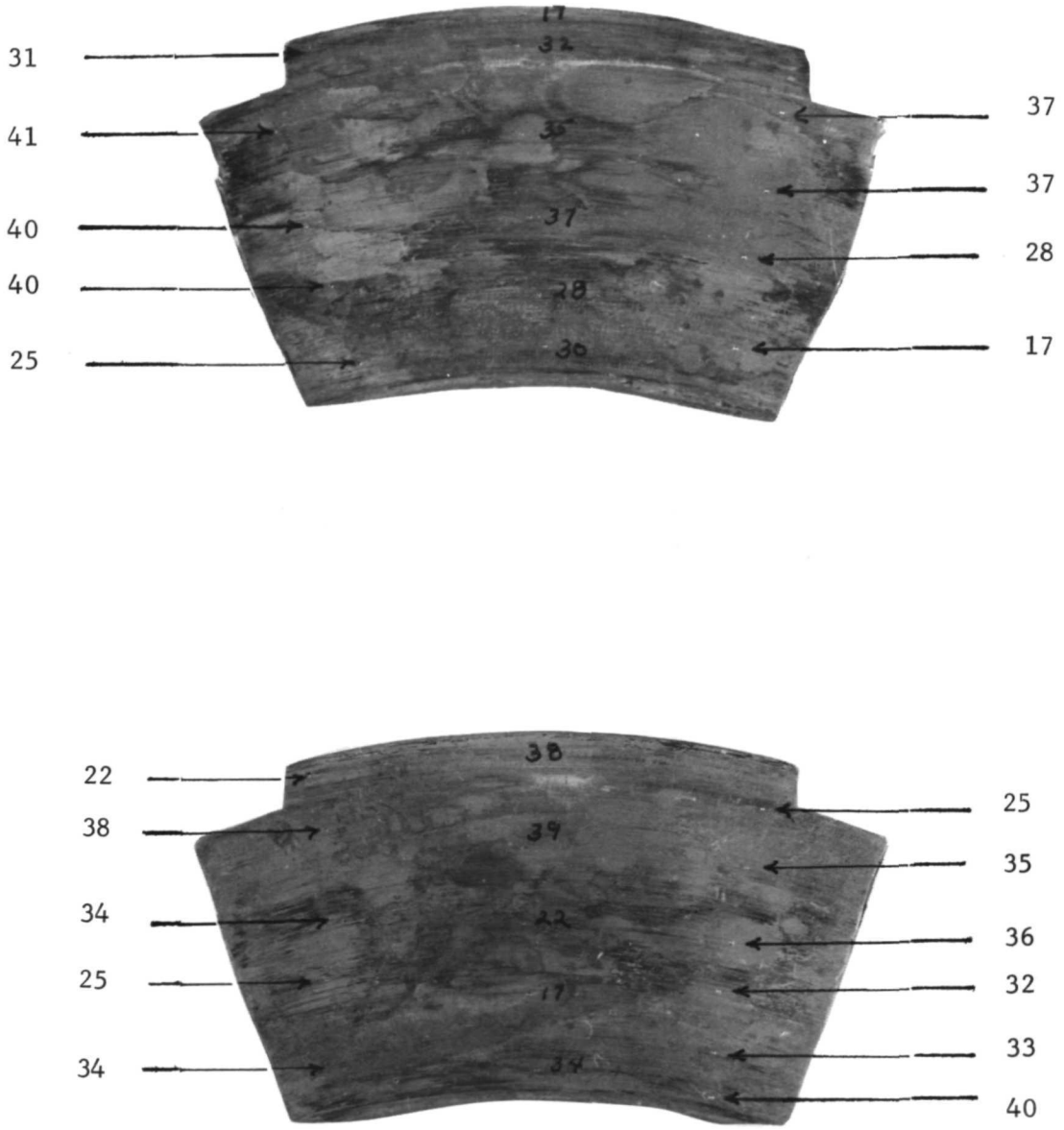


Figure 22. Photographs of Portions of Two Steel Disks and the Location of the Rockwell C Hardness Readings

oxidation product is constantly being worn away on the steel; therefore it remains thin. It was noted that the steel discs contained several cracks on the surface. Sections were taken through the disk and observed under the microscope. Upon metallographic examination it was noted that severe oxidation had occurred on the walls of the crack. It was also noted than an intermetallic compound had precipitated in the area of the crack. (This was probably the reason for the steel cracking.) This phase is probably a compound of chromium, molybdenum and silicon with carbon which forms at temperatures between 650°C and 870°C. Photomacrographs and photomicrographs of the steel disk are shown in Figure 21. This evidence shows that the temperature at the interface does indeed reach temperatures above 650°C.

The hardness of the steel disk was measured at several places to determine any variation which would also indicate the surface temperature. Two used disks were measured and found to have hardness variation of between 17 RC and 40 RC. In order to reduce the hardness of this material (17-22 AS) to 27 RC, the material has to be tempered at 700°C. Since the hardness of this disk varied below 27 RC, it is evident that the disk had to be heated to above 700°C to reduce its hardness. Figure 22 shows photographs and the hardness readings taken of the disks described above.

The results of the examination of the used pads confirms the fact that considerable oxidation is produced by frictional heating. However, the oxide is distributed throughout the material rather than at the interface. The oxide at the interface is very thin. In addition, it was observed that cracks occur in both the friction material and between the friction material and its steel container.

Many spalls of material are noted on the surface which probably results from the differential expansion of the friction material. This would also increase the surface temperature by decreasing the contact area.

Indications have been found that the bulk disk temperatures reach temperatures above 700°C which causes appreciable reduction in hardness. It was also found that the pad wore more heavily at the center than on the edges.

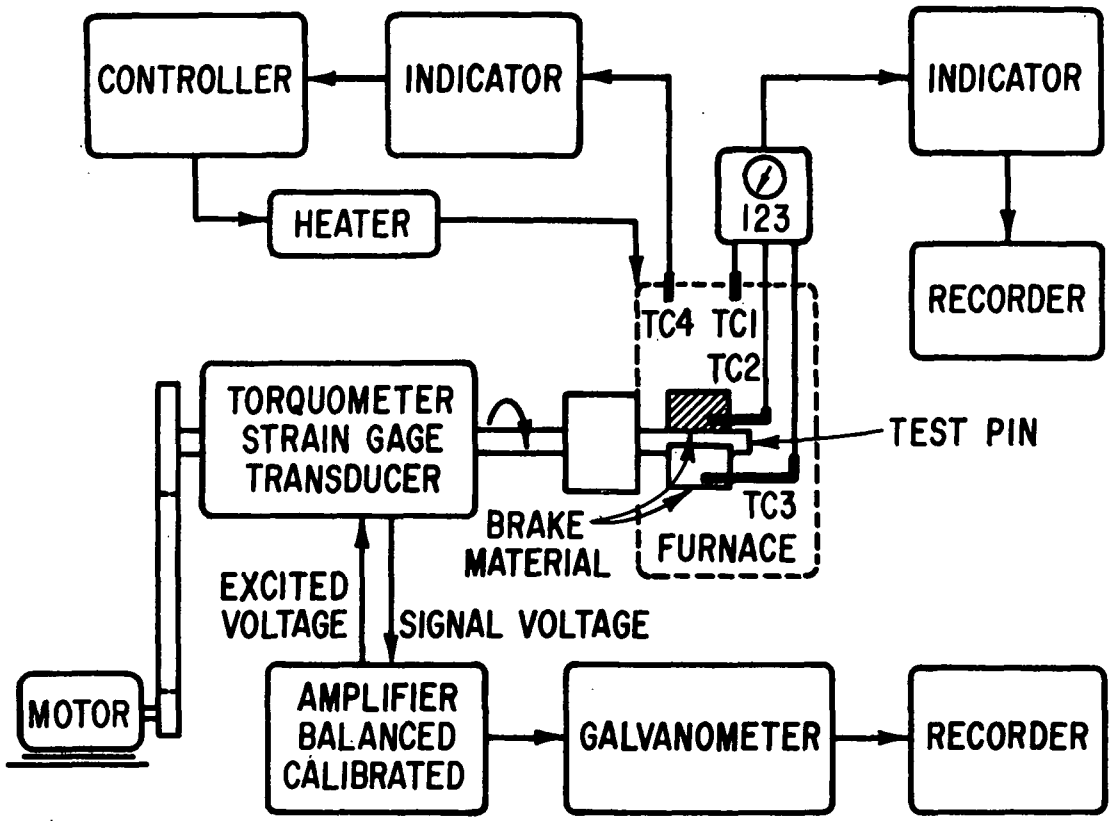
3.4 Frictional Behavior of Brake Materials

3.4.1 Introduction

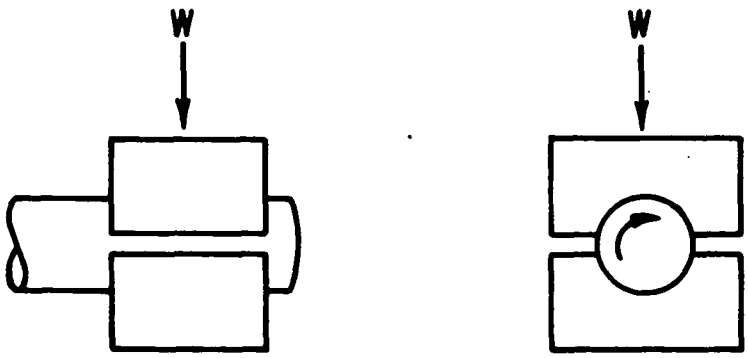
As was previously discussed, the friction-temperature behavior is a critical consideration in the development of brake materials. It is even more significant from the standpoint of safety. What is desired is to find or develop materials which will give constant friction to extreme temperatures. As a first step in this process it is desired to develop an understanding of the frictional behavior of current brake materials to see what improvements, if any, are needed. Secondly, in the previous section it was found that the surfaces are covered with a thin oxide film. It is of interest to know if this oxide plays a significant role in the friction behavior of brake materials or not. Accordingly, a series of friction-temperature tests were run with various brake materials and various steels. The results of this investigation are described in the following sections.

3.4.2 Apparatus

A diagramatic sketch of the test rig used for this investigation is shown in Figure 23. Essentially, it consists of a rotating pin (.625 cn diameter) which is loaded between two conforming button specimens. The test pin is rotated by a motor through a gear box and a torque meter. The torque meter which continuously records the friction torque was previously calibrated with dead weights. The load is applied to the top specimens through a pivot so misalignment is prevented. A lever arm system applies dead weight loading on the pivot. Before the program began the load system was also calibrated with dead weights. The test specimens are enclosed in a test chamber. This chamber has provisions for an evacuation and introduction of a controlled atmosphere although these were not used in the present experiments. A heater was contained inside the chamber which allowed heating to 700°C. As shown in Figure 23, a total of four thermocouples were used. Thermocouple 1 measured the furnace temperature; thermocouple 2, the specimen temperature near the interface; thermocouple 3, the specimen temperature 1 cn from the interface; and thermocouple 4 was used to control the furnace. In the initial experiments it was found that thermocouple 2 and thermocouple 3 gave essentially the same temperature. Since thermocouple 2 was



TEST APPARATUS



TEST SPECIMENS

Figure 23. Diagram of Test Apparatus

extremely difficult to install it was eliminated and thermocouple 3 was used to determine the operating temperature.

Most of the experiments were run under a single set of test conditions. The velocity was 3.5 cn/sec with a load of 22.7 Kg (29 Kg/cn^2 on a projected area basis). Several other tests were run with loads up to 273 Kg. These conditions were chosen to minimize the generation of friction heat. Two types of test were generally run under these operating conditions. In one test, one-half hour runs were made at increasing temperature levels. In the second test the furnace temperature was gradually increased as the test continued till the maximum temperature was reached. In both cases friction was often recorded as the temperature was decreased.

In running the tests the following procedure was used. The specimens were first cleaned using the standard procedure of repeated applications of levigated alumina. They were rinsed with alcohol and placed in the test rig with stainless steel tongs. The load was applied and the test started. Friction was recorded for one-half hour at room temperature. The temperature was then increased by one of the methods discussed previously.

3.4.3 Simulation

It was not the intention of these experiments to simulate braking operations. Rather it was intended to record the friction-temperature behavior of the materials under controlled conditions. This information is to be used in providing friction values for the analytical studies and to determine if improvements can be made with current materials. It should be noted, however, that the test geometry shown in Figure 23 is similar to the brake in that both specimens are continuously in contact. That is, the pin is not exposed to the atmosphere or cooling during part of its cycle. This is the same sliding condition which exists in disk brakes.

3.4.4 Materials

The materials used in this study were all obtained from commercial sources. The composition and hardness of the pin materials are given in Table 2 and a description of the slider materials is given in Table 3.

TABLE 2

PIN MATERIALS

Material	Composition	Hardness
Copper	99.999%	-
SAE 4037 Steel	.37C	60 Rc
SAE 17-22AS Steel	.30C; 1.3 Cr	45 Rc
M-2 Tool Steel	.85C; 4 Cr; 6W; 5Mo	61 Rc
Al_2O_3	GE Lucolox	-
410 Stainless	.15C; 12Cr	92 Rb
440 Stainless	1.0C; 17Cr	58 Rc
303 Stainless	.15C; 18Cr; 9Ni	98 Rb
A-286	.08C; 15Cr; 26Ni	29 Rc
Inconel C	.20C; 15Cr; 68Ni	20 Rc

TABLE 3

SLIDER MATERIALS

Materials	Description
Copper	99.999%
SAE 1020 Steel	-
Cobalt	99.9%
CX	Bendix Copper Base Brake Material
CC	Bendix Copper Base Brake Material
Carbon	Supplied by NASA (PT 0275 Union Carbide)
WCU	Wellman Cu Base Brake Material
WFE	Wellman Fe Base Brake Material

These materials were ground to at least an 8 to 16 RMS finish before use.

A series of tests were run with these materials using the previously described test procedure. The results of these tests are described in the following sections.

3.4.5 Reproducibility

Initially a series of experiments were run to establish the reproducibility of the data and to compare the results using this apparatus with that of other investigators. Figure 24 shows the results for cobalt/SAE 4037 steel combination and SAE 1020/M-2 tool steel combination. For cobalt friction values of 0.36 to 0.47 were obtained after 1800 seconds. These are similar to values previously reported for cobalt (Ref.9). Because of the transfer much greater variations in friction were found for the steel/tool steel combination. However, this is expected and the values are similar to those which are found with steel when galling is taking place. In both these cases it is considered that adequate reproducibility is obtained.

In Figure 25 the friction-temperature results for the cu/cu combination is compared with those which have previously been reported by Buckley and Johnson (Ref.9), by Rabinowicz (Ref.10) and by Peterson (Ref.11). For these experiments the test machine was turned by hand (low speed) since it was not possible to obtain data when galling was taking place if the machine was run at normal speed. It can be seen that the results are similar and all predict a drop in friction at about 250°C. Friction values below this temperature are different, however this is expected with the cu/cu combination which experiences welding and metal transfer at low temperatures. Thus this apparatus is giving accurate friction results.

For comparison purposes the friction-temperature data is given for the SAE 4037 pin/SAE 1020 steel and the M-2 tool steel pin/SAE 1020 steel combination in Figure 26.

It can be seen that for the 4037 pin/1020 steel combination the friction is high, up to approximately 250°C where it drops to a value of 0.50.

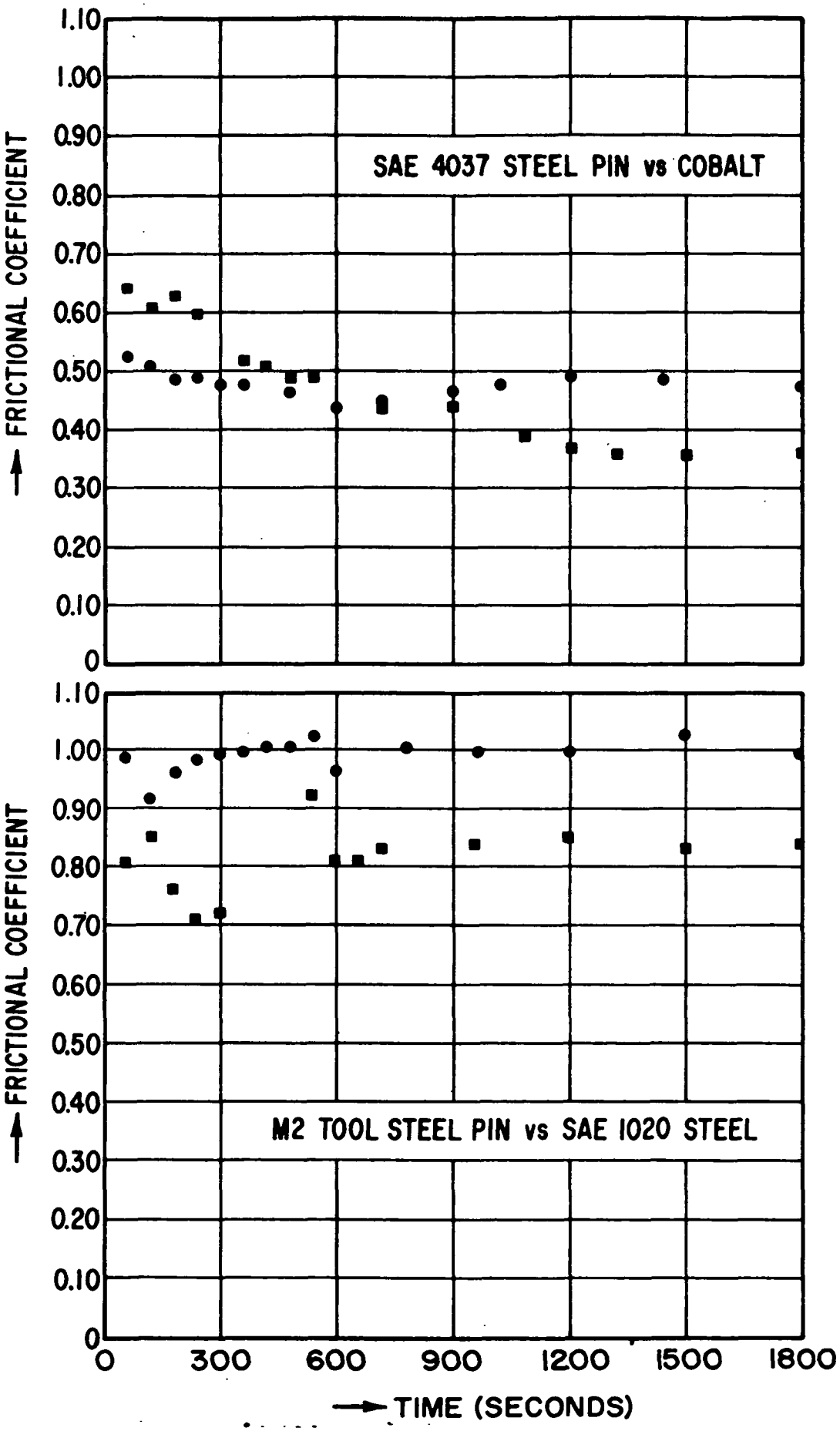


Figure 24. Effect of Sliding Time on Friction Coefficient. Load, 22.7 Kg; Velocity, 3.5 cn/sec; Temperature, 26° C

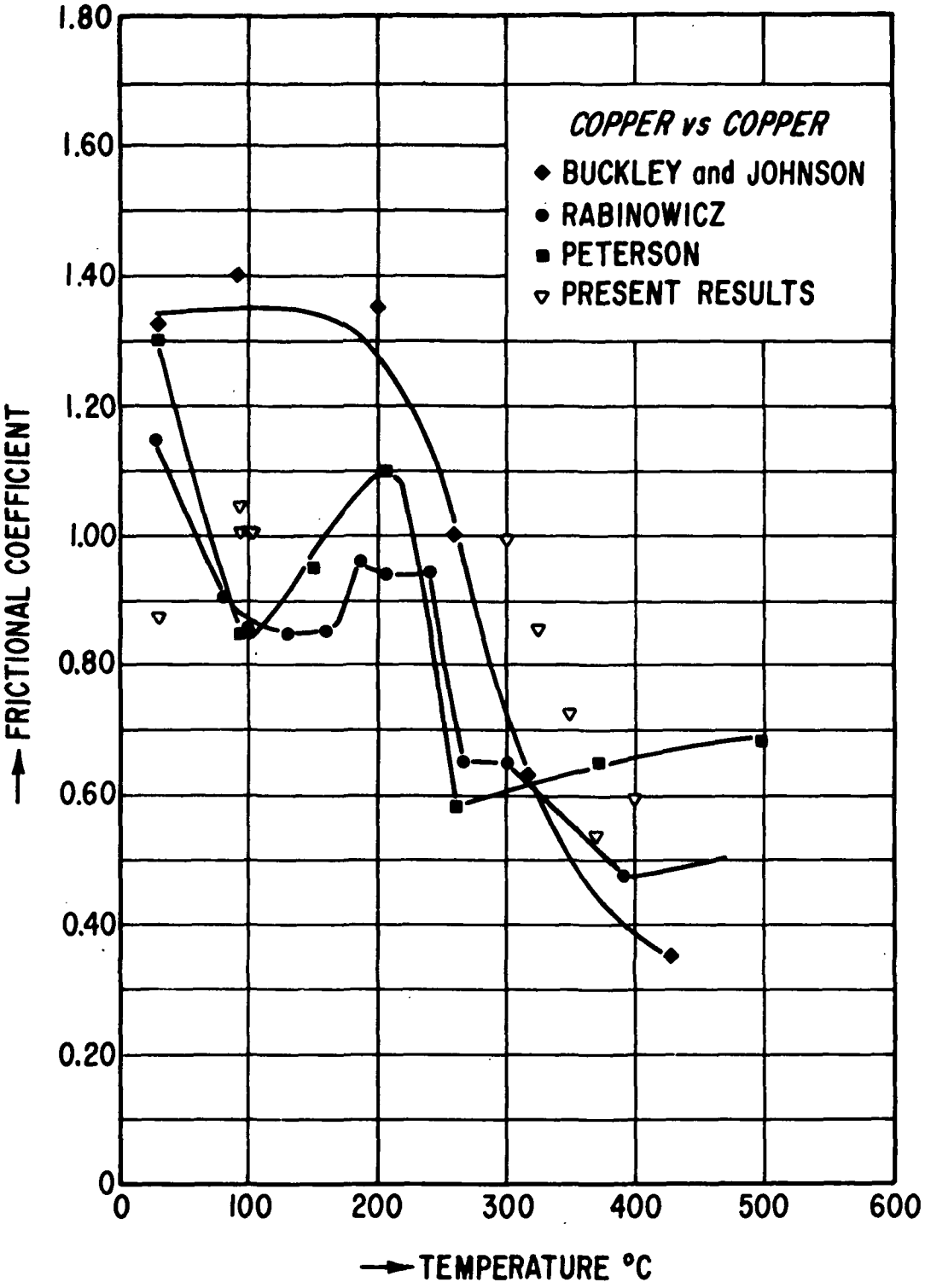


Figure 25. Effect of Temperature on the Coefficient of Friction for Copper Sliding Against Copper

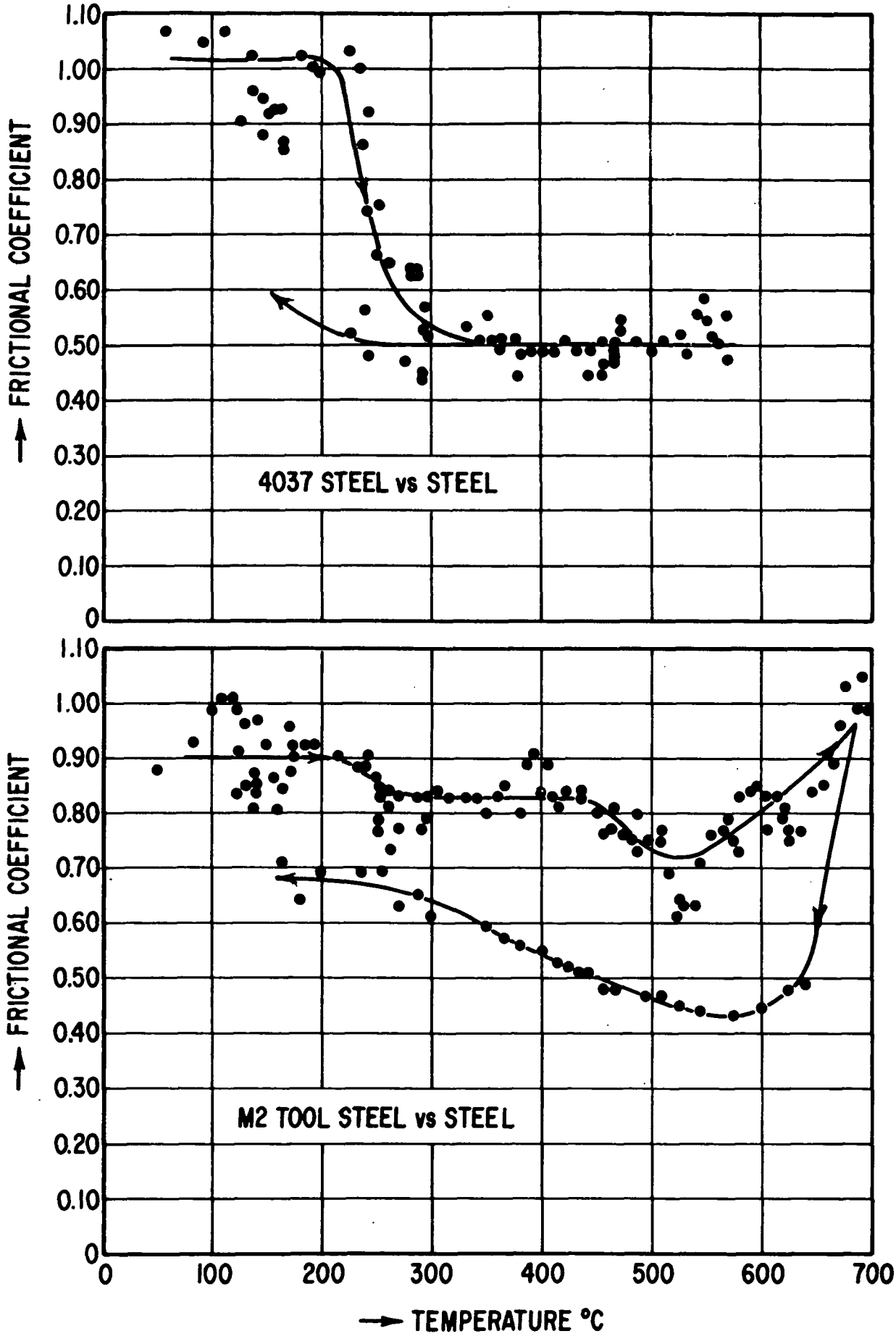


Figure 26. Effect of Temperature on the Friction Coefficient for Steels. Load, 22.7 Kg; Velocity, 3.7 cn/sec; Temperature, 26°C

Above that temperature friction remains constant at 0.50 to approximately 650°C. This drop off is undoubtedly due to the formation of surface oxides. Upon cooling lower temperatures can be reached before friction increases. No direct comparison data could be found; however, the data for 1020/1020 of Ref.(11) show that the drop in friction occurred at about 100 to 125°C. Thus it appears that under the conditions of the present experiments higher drop off temperatures due to oxides are found. This would be expected from the much higher loads and from the continuous contact of the present geometry.

When an M-2 tool steel pin was substituted for the 4037 steel pin (equal hardness) there was some evidence of a drop off in friction around 250°C; however, friction remained relatively high with considerable variations up to 700°C. Upon cooling friction is lower and similar to the values for the 4037/1020 steel combination. It would seem reasonable to assume that the greater oxidation resistance of the M-2 tool steel prevented the friction reduction due to oxide formation.

3.4.6 Frictional Behavior of Brake Materials

The friction-time behavior for the CX and CC materials with SAE 4037 steel and with M-2 tool steel pins is shown in Figure 27. In all cases an initial rising trend was found. The reason for this is not known; however, it is likely a result of residual surface contamination; the porous brake materials were almost impossible to clean. However, later experiments, run after high temperature operation, occasionally gave a similar trend but more often gave a constant value in the 0.70 to 0.90. In a longer term test the friction coefficient initially increased to a value of 1.07, decreased to .80 and then leveled off at a value of 1.08. This shows that there can be considerable variation in friction during room temperature operation. Also shown in this figure is the specimen temperature (1 cn from surface). It increases due to frictional heating to a temperature of approximately 120°C during the test.

The effect of temperature on the friction coefficient for CX and CC brake materials versus the 4037 steel pin are shown in Figure 28. The temperature plotted in these graphs and in all others is the specimen temperature,

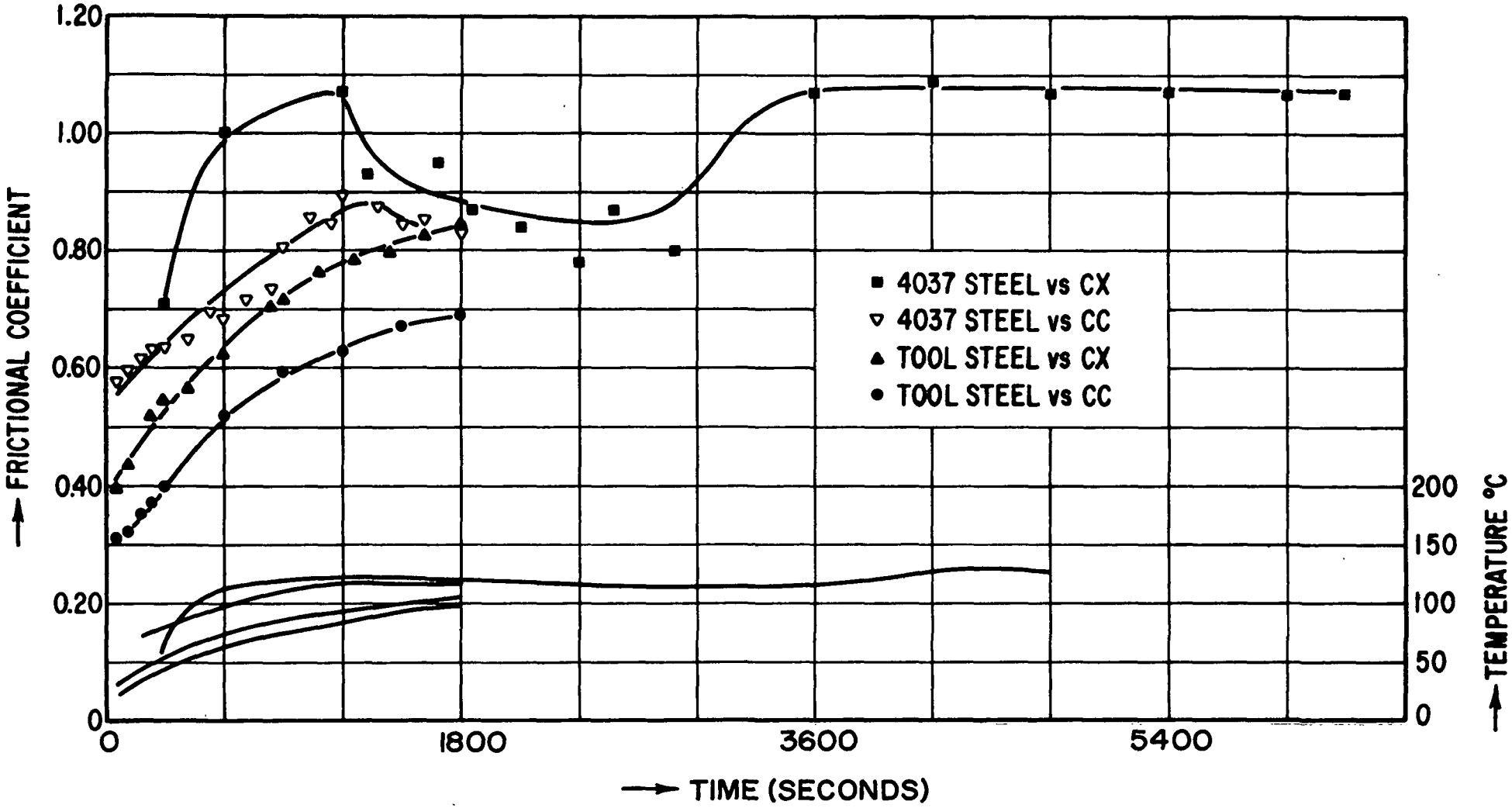


Figure 27. Effect of Sliding Time on the Friction Coefficient for Brake Materials. Load, 22.7 Kg; Velocity 3.5 cn/sec

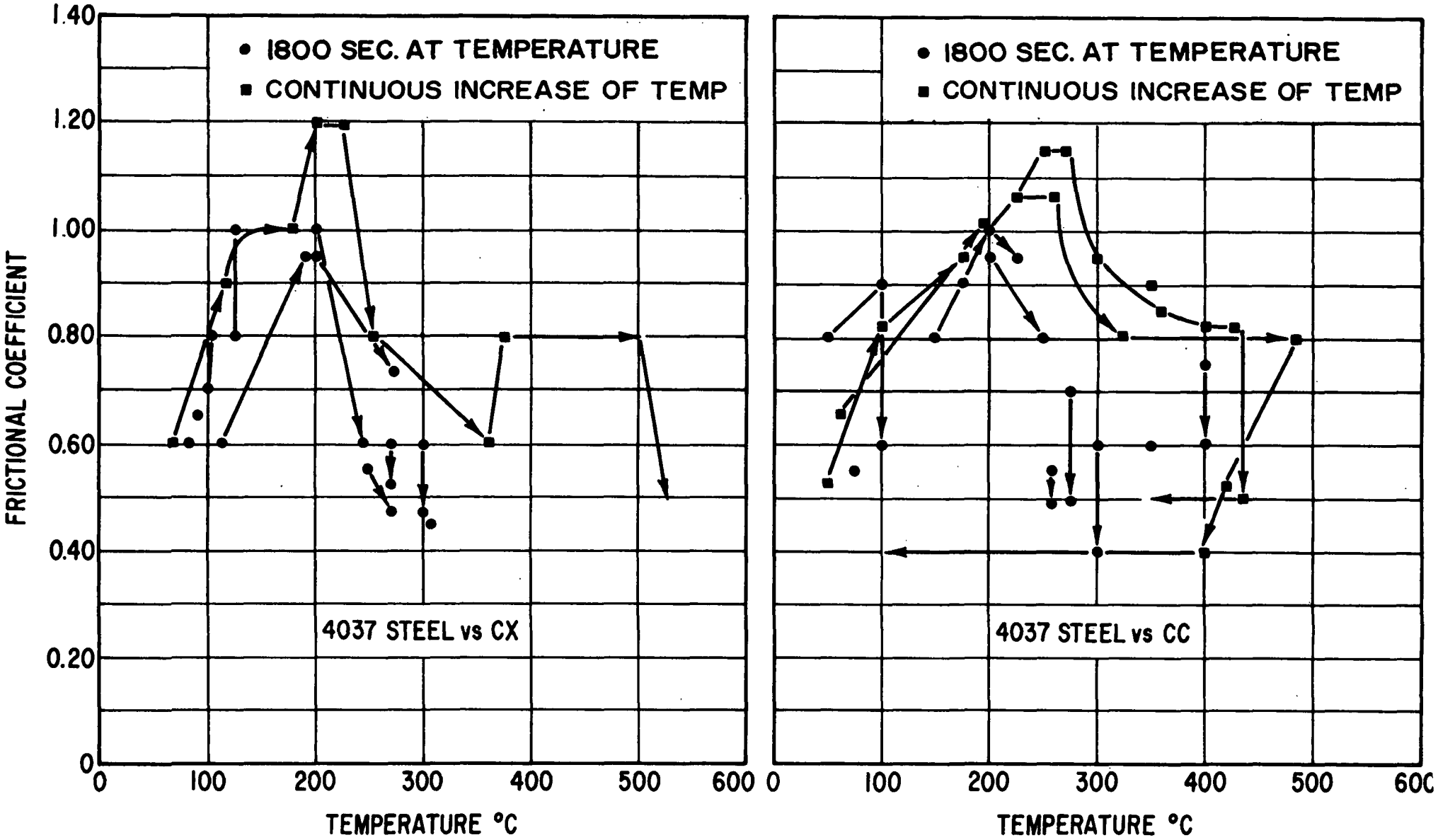


Figure 28. Effect of Temperature on the Coefficient of Friction for Brake Materials. Load, 22.7 Kg; Velocity 3.5 cn/sec.

not the furnace temperature. The two types of tests are shown, the 1800 second (1/2 hour) at temperature and the continuously increasing temperature. The arrows represent the change in friction with temperature. In the 1800 second (1/2 hour) tests the specimen temperature often increased, due to frictional heating, during the course of the test run. Therefore, both the temperature and the friction change over a short interval as indicated by the arrows at a particular temperature.

These curves show the following characteristics:

- Both materials have very similar frictional behavior.
- Friction increases with temperature up to 200°C and decreases above this temperature.
- 1800 second tests gave lower friction (.40 to .60) above 200°C while continuous heating higher friction (.80 to .90) was maintained to 400°C to 500°C.
- Cooling gave constant friction of .40 to .50.

Qualitatively these results can be simply explained as follows: The friction, when the oxide film predominates, is .40 to .50 and when metal contact exists approximately 1.00 or higher. With continuous heating a stable oxide is more difficult to form so friction remains high to higher temperatures. However, in the 1800 second test sufficient time is available during heating to form the surface oxide. Thus the lower friction with the 1800 second test is understandable.

Since the materials are similar it would be expected that they would have similar friction values, as they do. The initial increasing trend is the same for both materials. It was felt that since several of the 1800 second tests showed, on certain occasions, a decreasing trend at low temperatures that the rate of heating may be influencing this initial temperature rise. Accordingly, a comparison was made between rapid heating and slow heating. It can be seen (Fig.29), however, that the heating rate did not make any difference. The actual specimen temperature, not the heating rate or the furnace temperature, determines the friction coefficient.

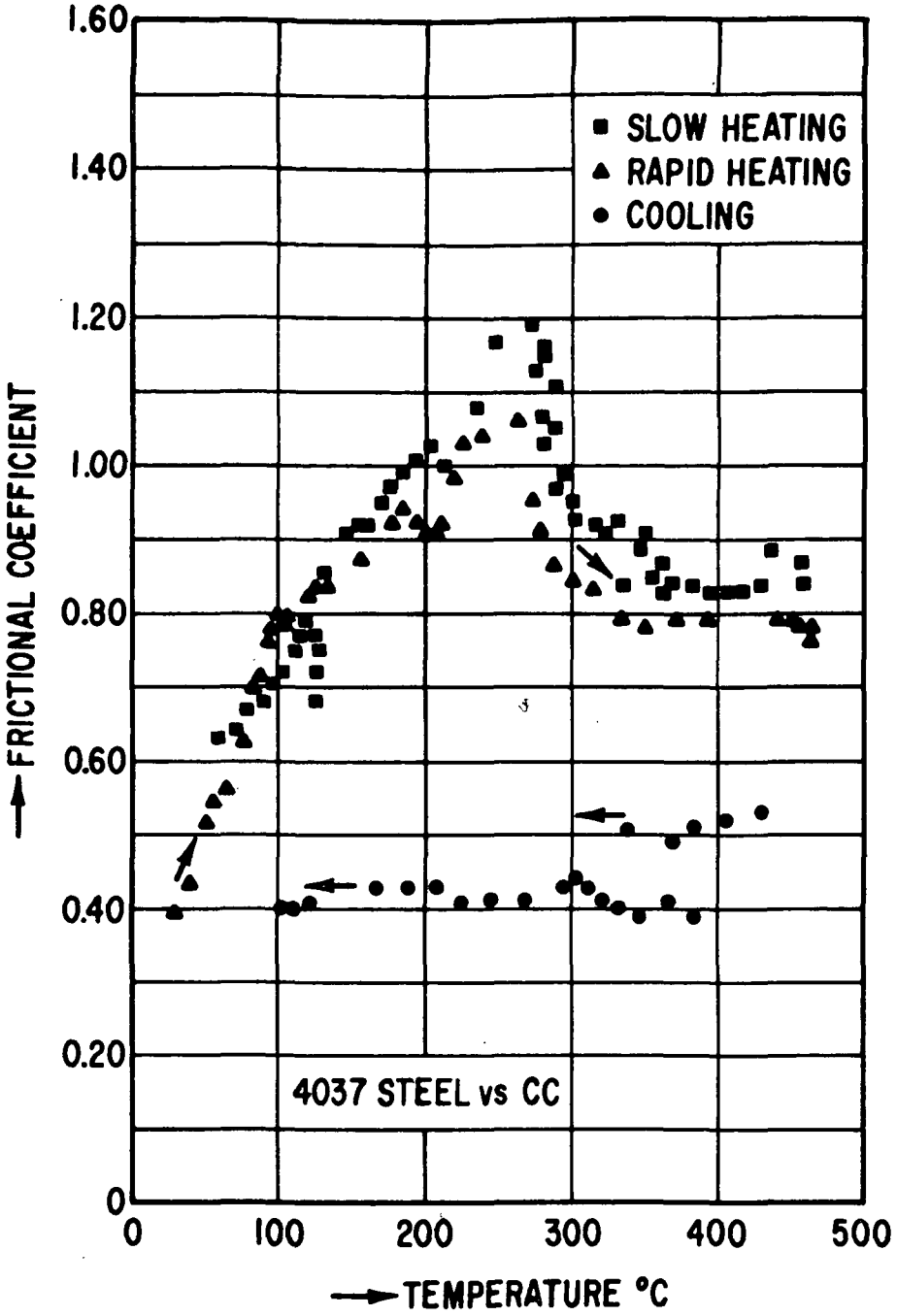


Figure 29. Effect of Temperature on the Friction Coefficient for Different Heating Rates.
Load, 22.7 Kg; Velocity, 3.5 cn/sec.

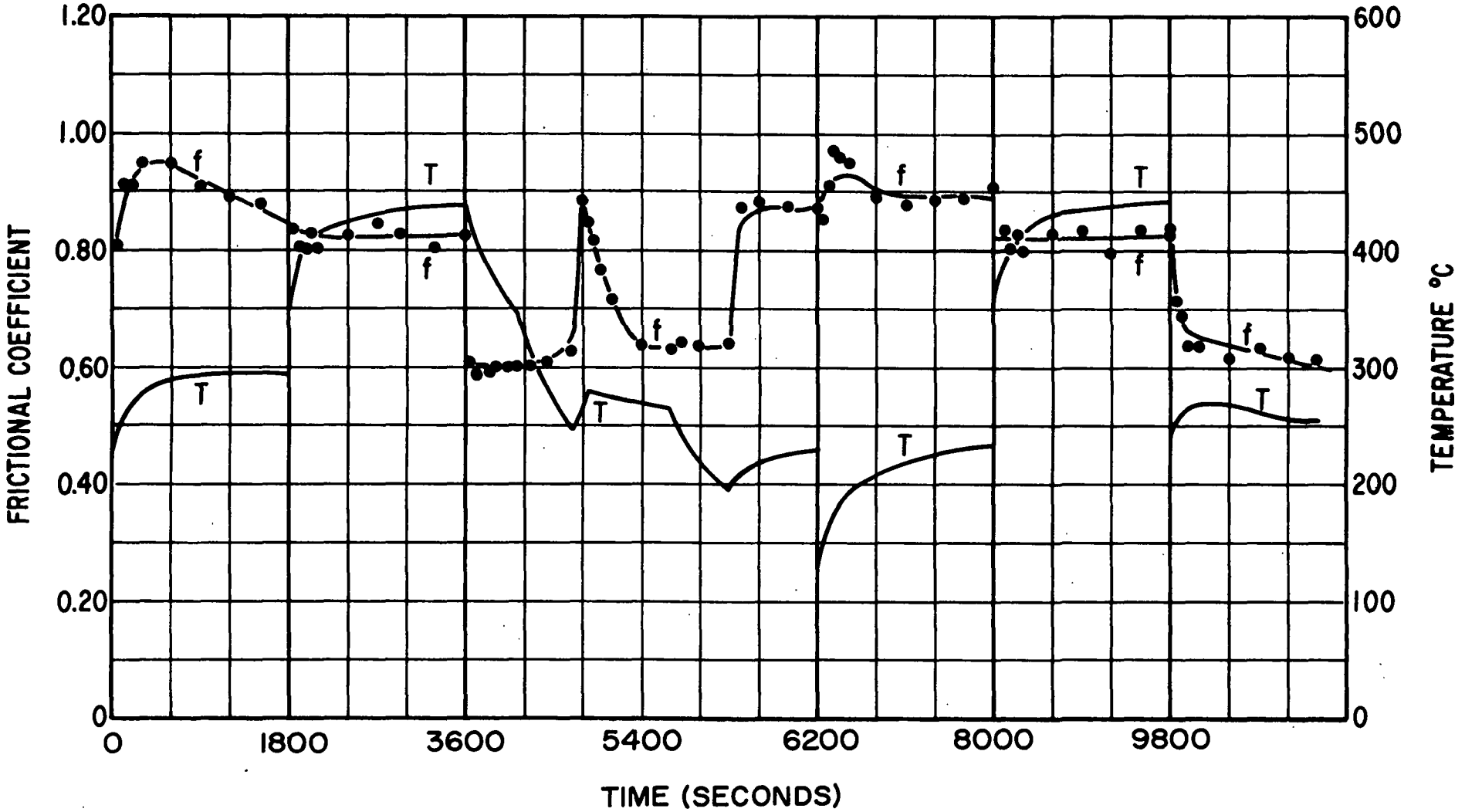


Figure 30. Effect of Changes in the Specimen Temperature on Coefficient of Friction for the M-2 Tool Steel - CC Brake Material Combination. Load, 22.7 Kg; Velocity, 3.5 cn/sec.

Two further questions can be asked:

Is the reduction in friction at 250°C due to the oxidation of the steel pin or the brake material?

What is the cause of the large differences in friction between heating and cooling?

The first question is difficult to answer based upon the previous data since both steel and the copper showed friction reduction in the same temperature range. However, some further insight into both of these questions was answered in several succeeding experiments.

In Figure 30 the friction behavior is shown as a function of time. Also shown in the same figure is the specimen temperature behavior as a function of time. The results show that whenever temperature is increasing friction increases and whenever temperature is constant or decreasing, friction is reduced. Since it is known that many oxides are easily removed from the surface and are more mechanically stable at the temperature at which they are formed, a hypothesis can be made as to the reason for this behavior. When heating the metal expands faster than the oxide and causes tensile stresses in the oxide cracking it. Upon cooling, however, the oxide would be in compression and would resist fracture. Thus metal friction values are associated with increasing temperatures and oxide friction values with constant or reducing temperatures. If the effect is true and it is general, it could have practical significance in brake behavior.

In order to determine if the effect was general a test was run with 17-22 AS steel. This is the actual rotor disk material. These data are shown in Figure 31. The figure includes both continuous heating and one-half hour testing. These data show many interesting trends, however, the most significant is that the friction behavior is completely different from that of the 4037 steel. Furthermore, a smaller friction difference in heating and cooling is noted. This implies that the frictional behavior is determined by the steel rather than the brake material and that the large differences in heating and cooling are also a function of the steel.

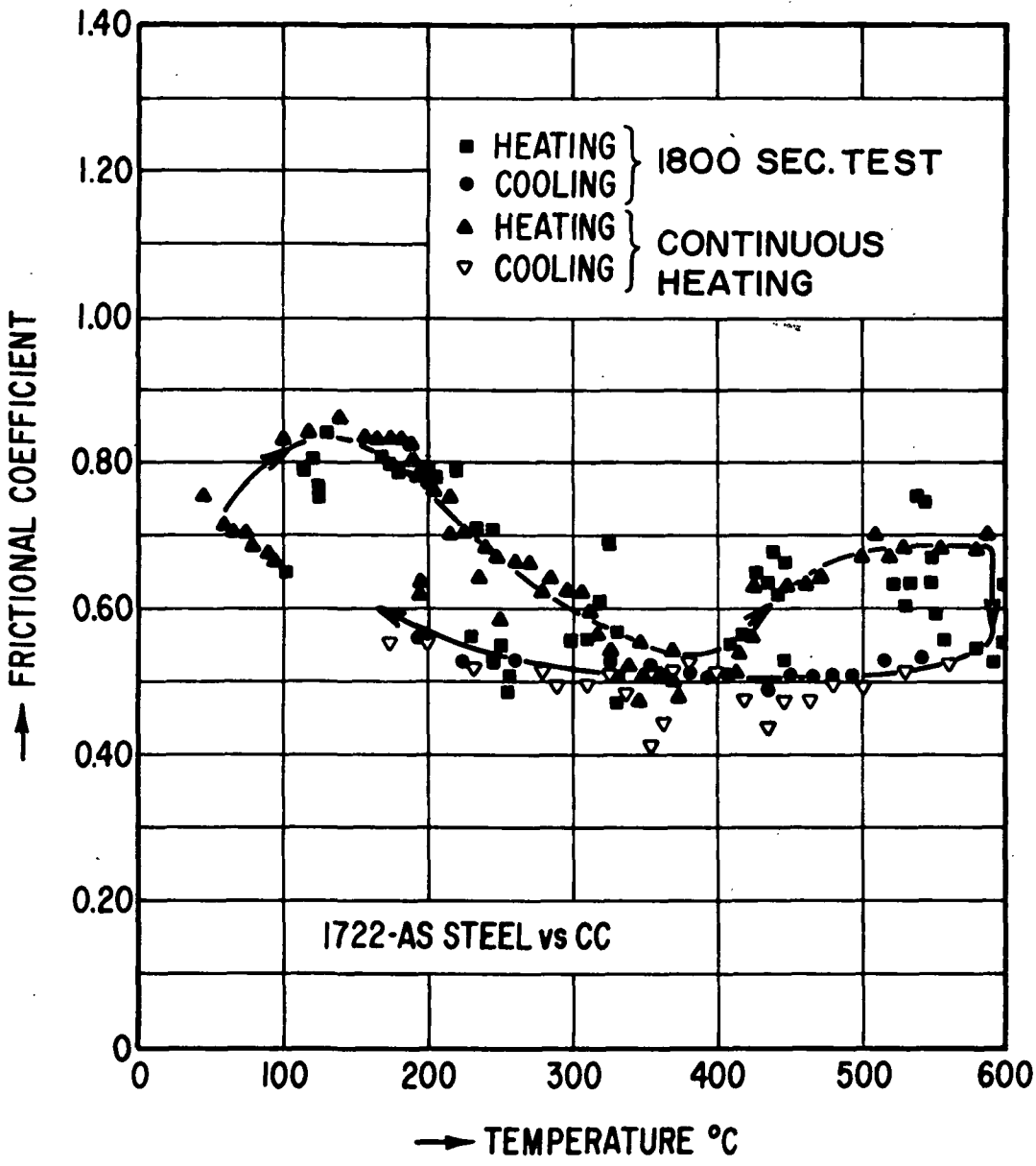


Figure 31. Effect of Temperature on the Friction Coefficient for the 1722-AS Steel - CC Brake Material Combination. Load, 22.7 Kg; velocity 3.5 cn/sec.

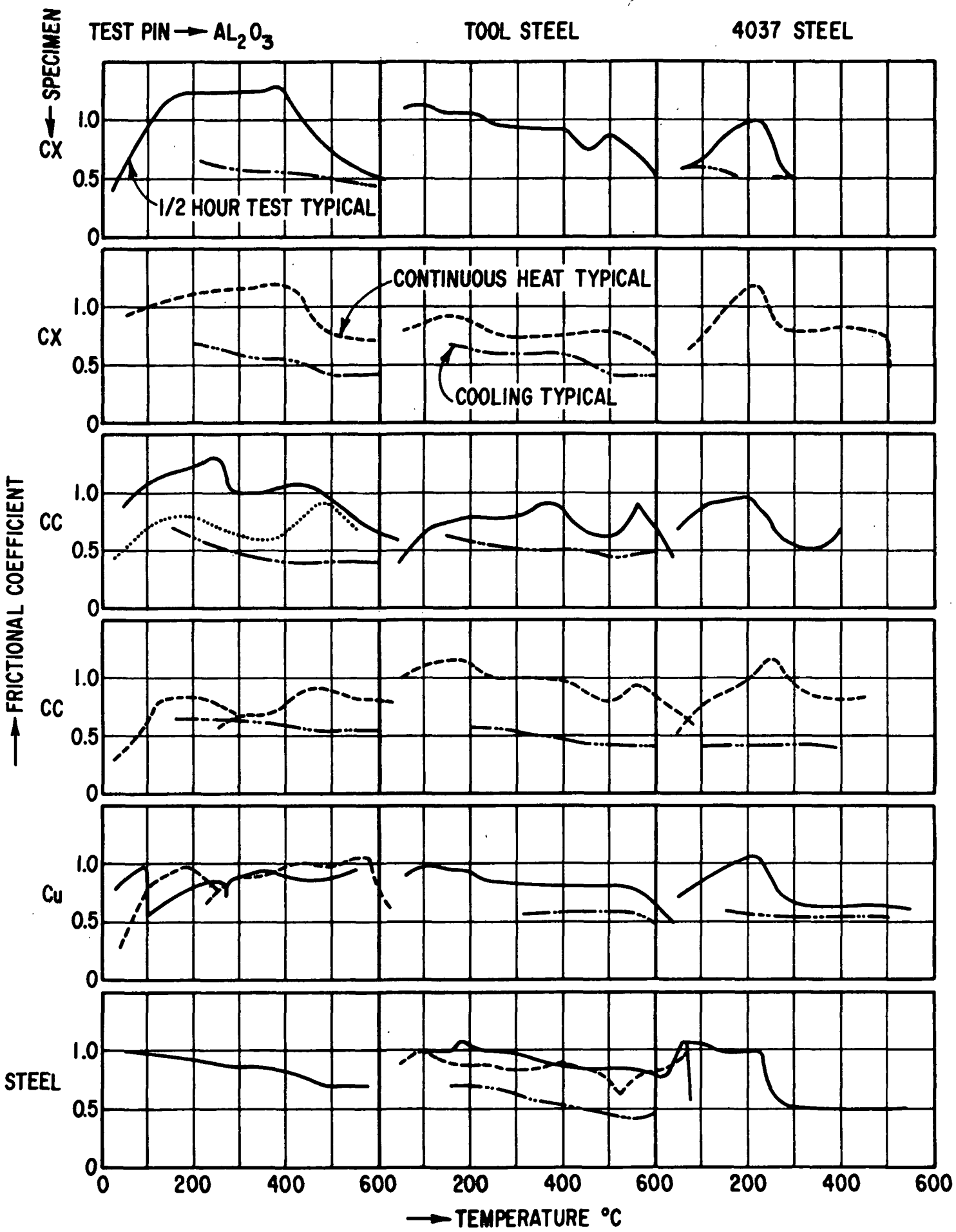


Figure 32.. Effect of Temperature on the Friction Coefficient for Various Test Pin - Slider Materials. Load, 22.7 Kg; Velocity, 3.5 cn/sec.

In order to check this effect further additional tests were run with M-2 tool steel, SAE 4037 and aluminum oxide pins. These data plus some of the previous data are shown in Figure 32. Each column represents a single pin material and each row a different slider specimen. It can be seen that a similar friction behavior is obtained with each steel pin regardless of the slider materials; this is true of the brake materials, as well as pure copper and SAE 1020 steel. It can also be seen that there is very little comparison between friction of the two steels even on the cooling portion of the cycle. Furthermore, these curves are different from the friction temperature curve of the 17-22AS steel of Figure 31.

It would be desirable to run with the brake materials sliding against themselves for comparison purposes. However, this was not possible since pins of brake materials were too fragile. Rather an alternative scheme, that of using a dense Al_2O_3 pin was used. These data were obtained since it has been shown (Ref.12) that when a metal slides against Al_2O_3 transfer occurs and the friction is the same as the metal sliding against itself. Although this is an assumption, it can be seen that in this case each slider material sliding against Al_2O_3 gives a different friction behavior. Furthermore, its behavior is completely different from the same material when run with steel. Whether this is actually the friction of the slider against itself may be questioned. However, note that with the brake materials and copper there is an increasing friction trend at low temperatures. This is also found with the 4037 steel and to a lesser extent with the tool steel. It is possible that this increase is due to the copper. It is not evident in the 4037/1020 steel test.

From these data the previous question may be answered with somewhat more assurance. The friction coefficient under these particular conditions is a function of the steel rather than the brake materials. The only influence which might be attributed to the brake material is the increasing trend at lower temperatures. Furthermore, some steels do not show the large differences between heating and cooling. The more oxidation resistant tool steel maintained higher friction to higher temperature.

3.4.7 Frictional Behavior with Oxidation Resistant Steels

In the previous section it was shown that the more oxidation resistant M-2 tool steel maintained higher more uniform friction at higher temperatures than did other low alloy steels. To study this behavior further, tests were run with a series of oxidation resistant alloys. These are shown in Figure 33. The data for continuous heating and 1800 second tests are both shown. It can be seen that although the same material (CX) was used as a slider, a whole variety of friction-temperature curves were obtained. The more oxidation resistance alloys such as Inconel C gave lower friction at lower temperature with an increasing trend at higher temperatures. The low alloy steels, although they gave different curves, did give similar trends as shown in Figure 34. Friction began to drop off in the 200°C to 250°C range. However, the more oxidation resistant steels (440°C) gave higher friction values. Thus these tests confirm the results with the tool steel.

3.4.8 The Effect of Load

All of the previous tests were run at 22.7 Kg load. Although this is a low load it does yield a high pressure 3×10^4 gm/cn^2 on a projected area basis. In an actual brake pressures of the order of 10^4 grams/cn^2 are used, however, one can never be sure that the entire pad is in contact and higher pressures could be obtained. In order to determine how this would affect friction, a series of tests were run at higher loads. The initial and the final values of friction are shown in Figure 35. It can be seen that the friction coefficient decreases with load.

3.4.9 Other Materials

Friction temperature curves were also obtained for other brake materials; these are shown in Figure 36. For the iron base materials friction is high, up to 300°C where it begins to decrease. The copper base material gives a constant value of .50 above 125°C. Upon cooling (data not shown) both of these materials gave friction values of .40 to .50.

The friction data for the carbon material was quite variable. In the data shown friction increased to .57 then gradually decreased to .20 as the

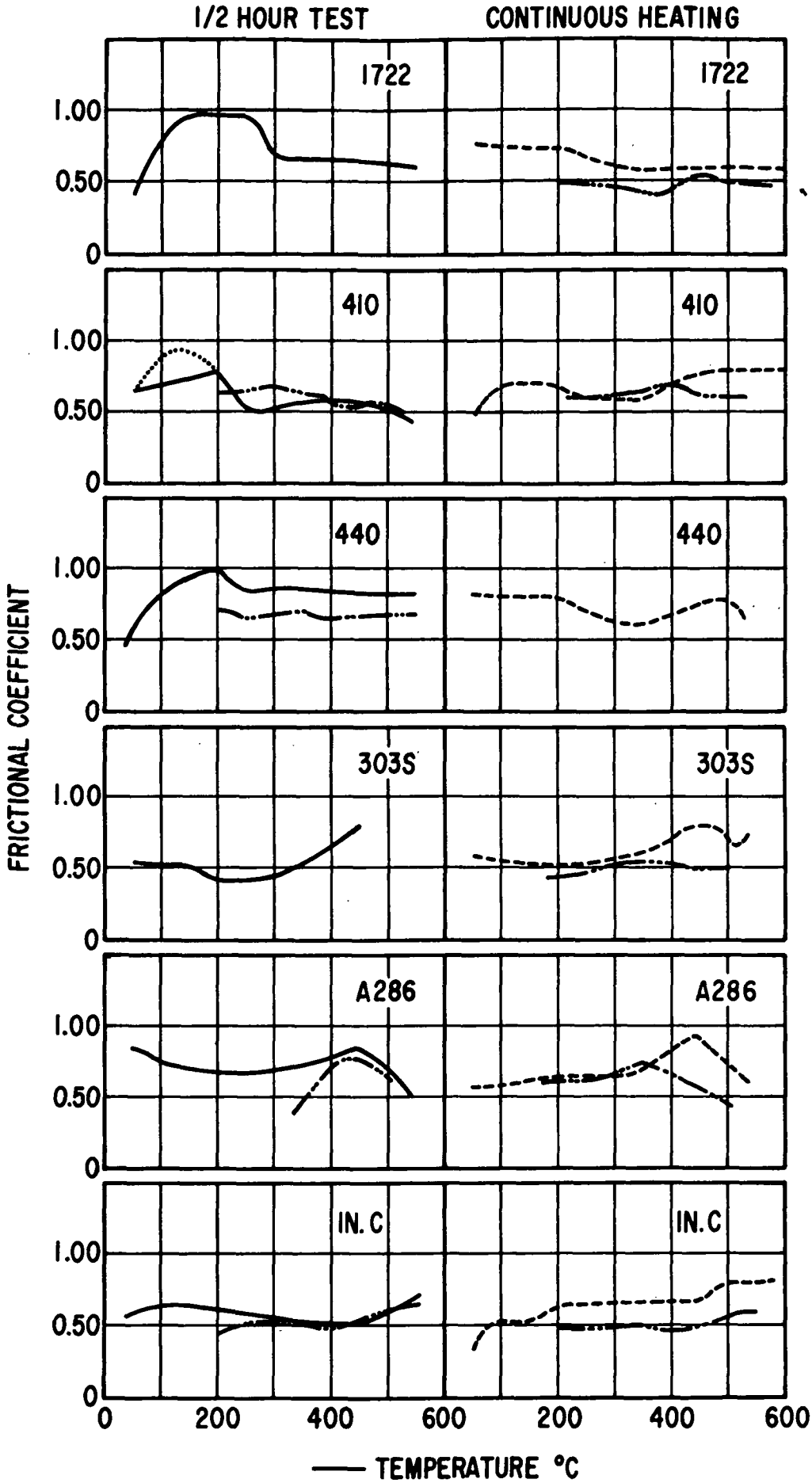


Figure 33. Effect of Temperature on the Coefficient of Friction for CX Brake Materials vs. Various Alloys. Load, 22.7 Kg; Velocity 3.5 cn/sec.

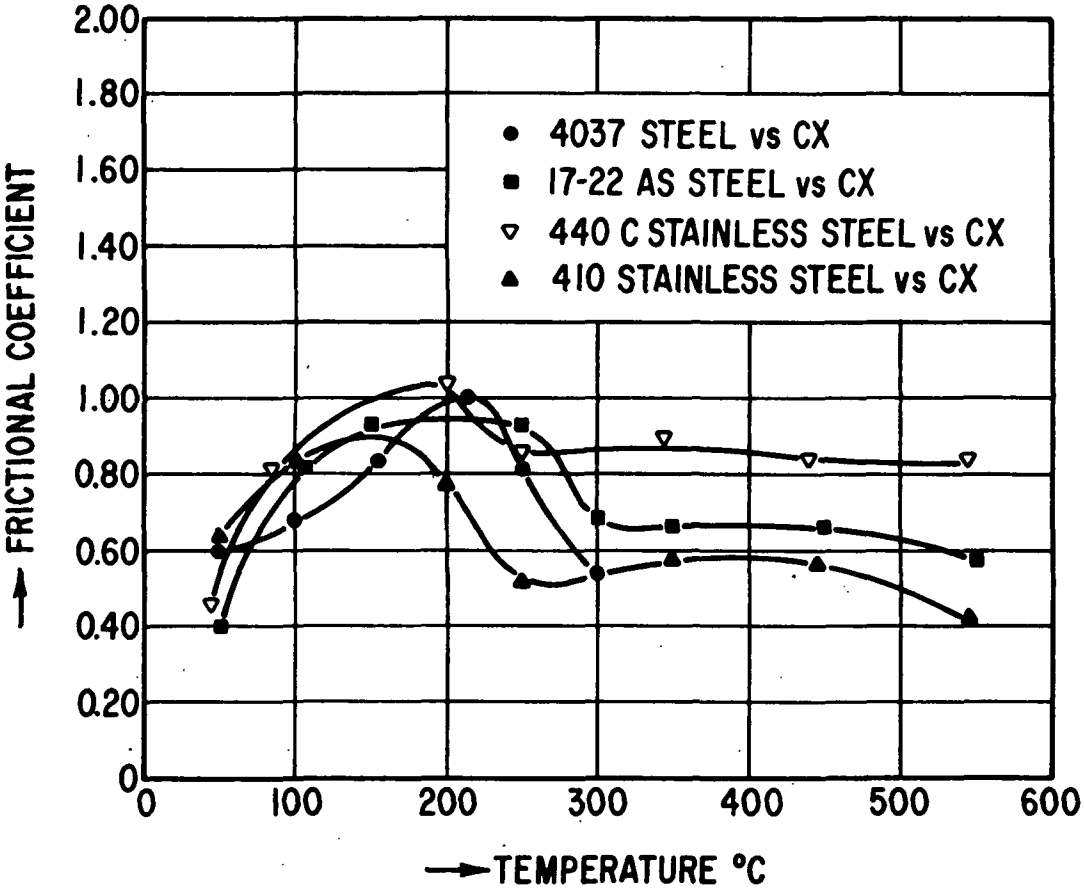


Figure 34. Effect of Temperature on the Coefficient of Friction for Various Steels Sliding Against CX Brake Materials. Load, 22.7 Kg; velocity 3.5 cn/sec.

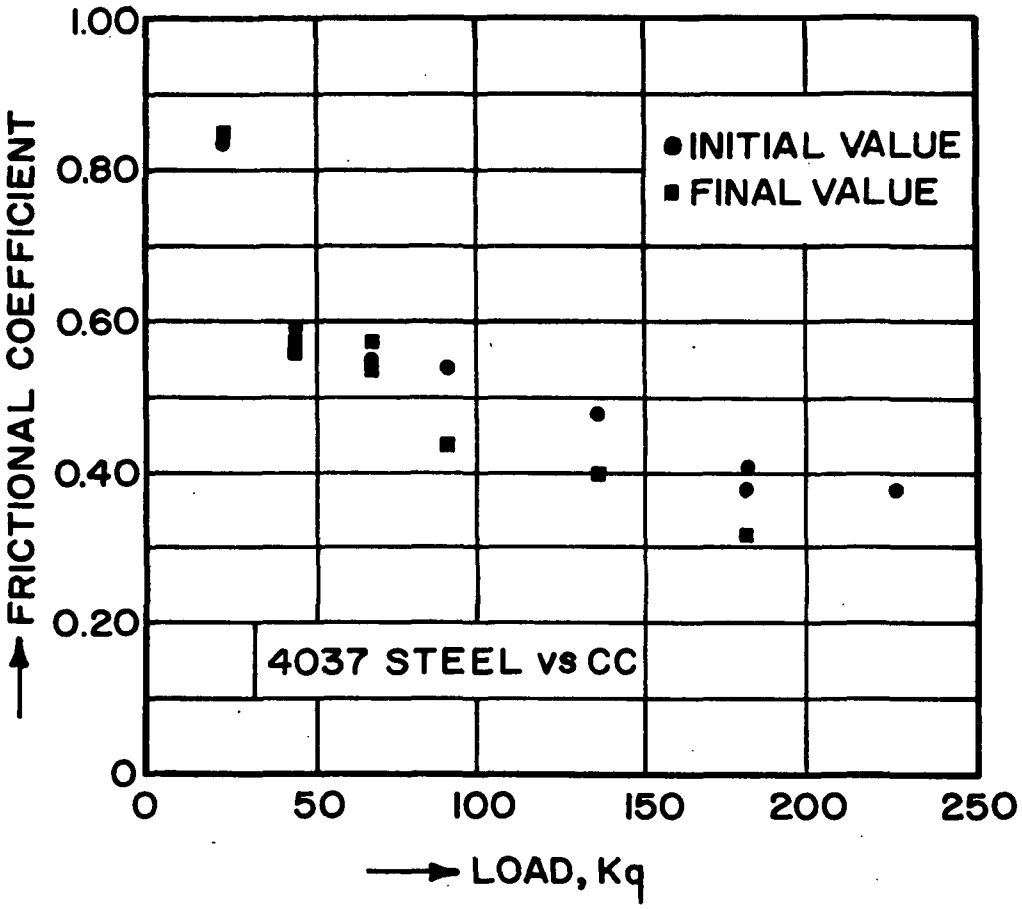


Figure 35. Effect of Load on the Coefficient of Friction of CC Brake Material.
Velocity, 3.5 cn/sec.

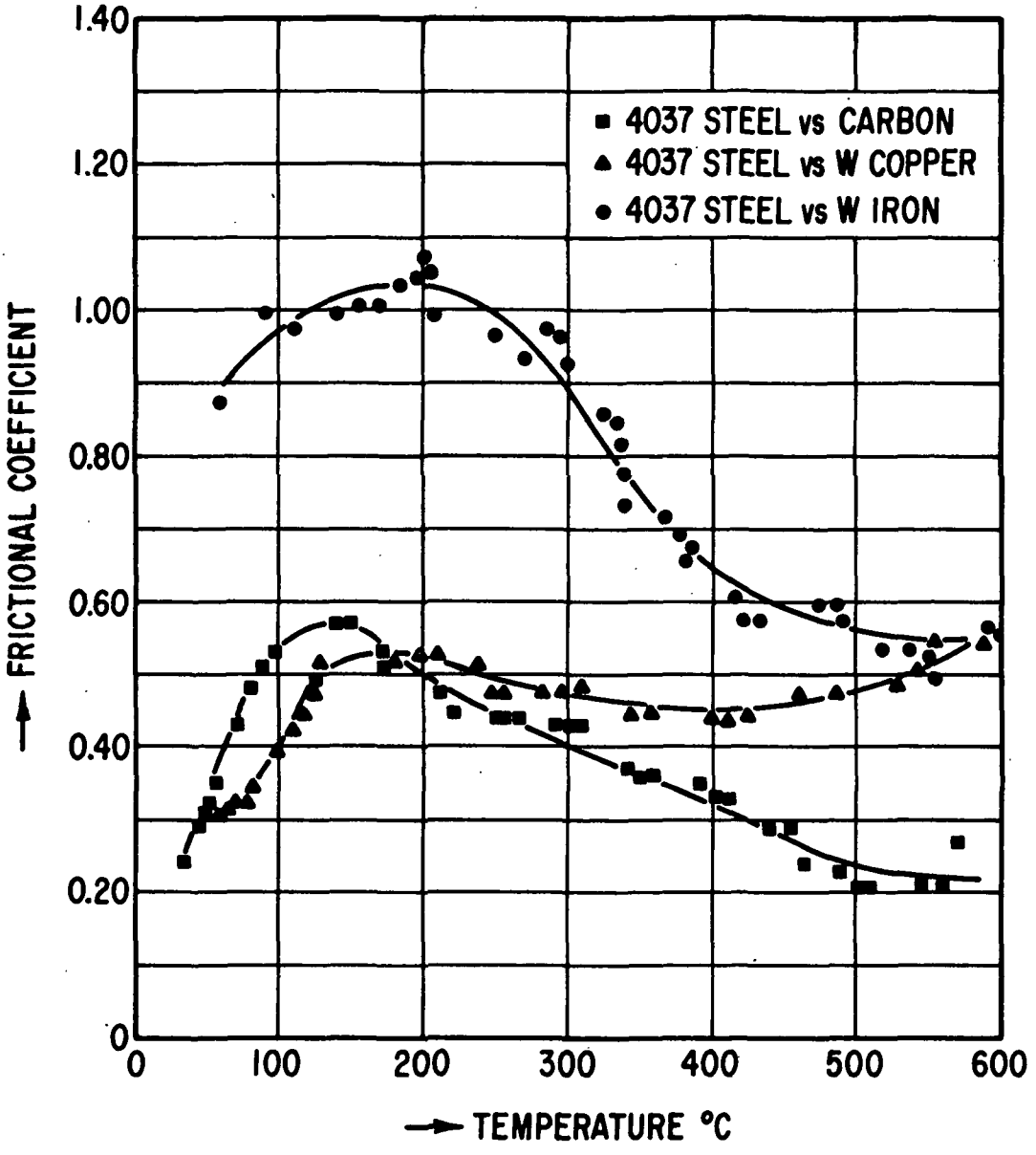


Figure 36. Effect of Temperature on the Friction Coefficient of Several Materials.
Load, 22.7 Kg; velocity 3.5 cn/sec.

temperature was raised. In other tests, however, the friction would be constant at .20 up to 400°C where it increased to .60. It appears that there are two levels of friction based on different surface conditions and that the friction varies between them.

The significance of these friction coefficients has not been determined. Further tests are necessary to determine the meaning of the trends.

SECTION 4

SUMMARY OF RESULTS

An exploratory study was conducted to determine what improvements could be made in the present aircraft brake materials particularly with regard to improving the friction and wear behavior and in minimizing the surface temperatures.

A consideration of the factors involved indicates that frictional variation at high temperature could result from three different phenomena; softening of the material which yields metal transfer and high friction, formation of oxides which reduce friction and surface melting which also reduces friction but greatly increases wear. New materials should retain their hardness and be oxidation resistant to higher temperatures than present materials. Metal transfer at high temperatures can be avoided by proper additive selection or by use of materials which formed suitable lubricating oxide films. Higher melting point materials would be desirable to prevent surface melting and low friction.

A simplified analysis was conducted in order to determine the factors which affect surface temperature. It was found that minimum surface temperatures would result under the following conditions:

(1) Use of materials with minimum values of $\left(\frac{1}{\rho c}\right)$ and $\left(\frac{1}{k\rho c}\right)^{\frac{1}{2}}$

k = conductivity; ρ = density; c = specific heat.

(2) When there is maximum contact area. This should result with materials with low thermal expansion, low modulus of elasticity, and low yield strength.

(3) The use of a higher load - lower friction system.

Where there are size and weight restrictions a criterion has been suggested for choosing the size of the brake disks. This criterion is that the quantity $\left(\frac{\alpha t_{max}}{\ell^2}\right)^{\frac{1}{2}}$ should be approximately equal to 1. (α = diffusivity; t_{max} is the braking time; and 2ℓ = disk thickness.) When greater thickness is used excess weight is being carried which is not being utilized in the

dissipation of heat; when smaller thicknesses are used the area must be made larger to maintain low surface temperatures.

Where the brake weight is restricted to a specific value then the specific heat is the most important factor in determining surface temperatures. Where the volume is restricted, it is the product of specific heat and density.

An investigation of used pads and rotors was conducted to determine the extent of oxidation and other factors relating to surface temperatures. It was found that the pad surfaces contained many cracks and material had spalled from the surface. This was attributed to the differential thermal expansion between the brake material and its container. It was found that there was only a very thin oxide film on the sliding surfaces, however there is oxidation of the copper particles in the matrix and on the steel container surfaces. It did not appear as if this could have a significant effect on surface temperatures under present braking conditions. Hardness tests on used rotor surfaces showed that there was considerable reduction in hardness due to the high temperatures. The bulk material would have to reach temperatures of 700°C or higher for this hardness reduction.

Bench test friction studies indicate that there is considerable friction coefficient variation with temperature. There is a large reduction in friction due to surface oxidation in the temperature range 250°C to 300°C. This friction reduction is associated with the oxidation of the steel surfaces. When oxidation resistant steels are used this reduction in friction is not evident up to 600°C. It was also found that the retention of the oxide film was a function of the temperature changes. With increasing surface temperature the oxide appears to be removed from the surface while with constant or reducing temperature the oxide is retained. The significance of this as far as brake operation is concerned was not established; however, it should be noted that the temperatures are changing through much of the brake cycle. The validity of these results are to be determined in pad friction tests currently being conducted.

The bench friction tests also showed that the friction behavior was determined by the steel surface rather than the brake material. Whether this effect is generally true is yet to be determined.

It is concluded that improved high temperature friction materials are desirable which have greater strength and generate lower surface temperatures. Three types of materials can be suggested.

(1) Non-porous alloys with high melting temperatures which do not transfer or gall due to formation of surface oxide film. (Surface oxides are kept thin by wear and should not interfere with conductivity.)
(2) Powder metallurgy products of high temperature materials.
(3) High temperature, low modulus, low expansion materials such as carbon, BN, and thermal shock resistant ceramics.

REFERENCES

1. Buckley, D. and Johnson, R.L., "Friction Behavior of Materials in Vacuum," Metals Engineering Quarterly, Vol.7, 1967.
2. Foley, R.T., Peterson, M.B. and Zapf, C., "Frictional Characteristics of Cobalt, Nickel and Iron as Influenced by Their Surface Oxide Films," American Society of Lubrication Engineers Transactions, Vol.6, p.29, 1963.
3. Peterson, M.B., Beretsky, I., Lewis, P. and Murray, S.F., "Study of Material and Design Modifications for Wear Improvements in the Sheave Spacers of an Arresting Gear Mechanism," MTI Report 64TR21, April 15, 1964.
4. Wu, J.J., to be published.
5. Carslaw, H.S. and Jaeger, J.C., Conduction of Heat on Solids, Oxford Press, Second Edition, p.112, 1954.
6. Newcomb, T.P. and Spurr, R.T., "Braking of Road Vehicles," Chapman & Hall Ltd., London 1967.
7. Barber, J.R., "Thermoelastic Instability in the Sliding of Solids," Proc. Roy. Soc. A, Vol.312, p.381, 1969.
8. Ling, F.F., "On the Thermal and Mechanical Effects at Sliding Interfaces," AFML TR 69-91, 1969.
9. Johnson, R.L., Swikert, Ma. and Buckley, D.H., "High Temperature Lubrication in Reactive Atmosphere," 16th Annual Conference, National Association of Corrosion Engineers, 1960.
10. Rabinowicz, E., "Lubrication of Metal Surfaces by Oxide Films," American Society of Lubrication Engineers Transactions, Vol.10, p.400, 1967.
11. Peterson, M.B., Florek, J.J. and Lee, R.E., "Sliding Characteristics of Metals at High Temperatures," American Society of Lubrication Engineers Transactions, Vol.3, p.101, 1960.
12. Peterson, M.B. and Lee, R.E., "Sliding Behavior of the Metal Ceramic Couple," Wear, Vol.7, p.334, 1964.